NO_x REDUCTION WITH THE USE OF FEEDLOT BIOMASS AS A REBURN FUEL

A Thesis

by

PAUL GORDON GOUGHNOUR

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2006

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee, Kalyan Annamalai
Committee Members, Jerald Caton
Saqib Mukhtar
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ABSTRACT

NO_x Reduction with the Use of Feedlot Biomass as a Reburn Fuel. (August 2006)

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Chair of Advisory Committee: Dr. Kalyan Annamalai

Coal fired power plants produce NO_x at unacceptable levels. In order to control these emissions without major modifications to the burners, additional fuel called reburn fuel is fired under rich conditions (10-30 % by heat) after the coal burners. Additional air called overfire air (about 20 % of total air) is injected in order to complete combustion. Typically reburn fuel is natural gas (NG). From previous research at TAMU, it was found that firing feedlot biomass (FB) as reburn fuel lowers the NO_x emission at significant levels compared to NG. The present research was conducted to determine the optimum operating conditions for the reduction of NO_x. Experiments were performed in a small scale 29.3 kW (100,000 BTU/hr) reactor using low ash partially composted FB (LA PC FB) with equivalence ratio (ϕ) ranging from 1 to 1.15. The results of these experiments show that NO_x levels can be reduced by as much as 90% - 95 % when firing pure LA PC FB and results are almost independent of ϕ. The reburn fuel was injected with normal air and then vitiated air (12.5 % O_2); further the angles of reburn injector were set normal to the main gas flow and at 45° upward. For LA PC FB no significant changes were observed; but high ash PC FB revealed better reductions with 45° injector and vitiated air. This new technology has the potential to reduce NO_x emissions in coal fired boilers located near cattle feedlots and also relieves the cattle industry of the waste.

DEDICATION

To my wife Laura and daughter Claire.

ACKNOWLEDGMENTS

I would like to thank my committee chair, Dr. Annamalai, and my committee members, Dr. Caton, and Dr. Mukhtar, for their guidance throughout the course of this research.

Thanks also to my friends in the Renewable Energy Lab who helped me with each of my experiments. I also want to thank the Texas Commission on Environmental Quality, which provided the funding for this research.

Finally, thanks to my wife and daughter for their patience, love, and support.

NOMENCLATURE

CO	Carbon Monoxide
CO_2	Carbon Dioxide
FB	Feedlot Biomass
HA	High Ash
HHV	Higher Heating Value
LA	Low Ash
NO	Nitric Oxide
NO_x	Nitrogen Oxides
PC	Partially Composted
RM	Raw Manure
SMD	Sauter Mean Diameter
SO_2	Sulfur Dioxide
TCEQ	Texas Commission on Environmental Quality
TXL	Texas Lignite Coal
WYC	Wyoming Subbituminous Coal

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INTRODUCTION

The United States Environmental Protection Agency reports that nitrogen oxides (NO_x) are one of the major air pollutants generated in the United States (Table 1). While the emission of these pollutants is on the decrease, several health and environmental concerns associated with NO_x such as respiratory problems, acid rain, poor water quality, and global warming call for even greater levels of reduction [1]. Due to the adverse affects of the presence of NO_x in our environment, strict regulations have been implemented in an effort to reduce the emission of these gases.

Table 1: Six principal air pollutants [2][3]

Pollutant	**2005 Emissions (Short Tons/year)**	**% Decrease in Emissions from 1993 to 2002**
Carbon monoxide (CO)	89,000,000	21
Lead (Pb)	3,000	5
Nitrogen oxides (NO_x)	19,000,000	12
Ozone (O_3)	Not Directly Emitted	Not Directly Emitted
Particulate matter (PM)	4,000,000	22
Sulfur dioxide (SO_2)	15,000,000	31

Coal fired power plants are a major contributor to the levels of NO_x in the environment. The EPA has set strict NO_x emission standards that coal fired utilities must meet. Phase II of the EPA's Acid Rain Program required NO_x levels for coal fired boilers to be below 0.46 lb/mmBtu by the year 2000[4]. After the implementation of the Clean Air Interstate Rule in 2009, power plants will be required to reduce NO_x emissions to below 0.15 lb/mmBtu[5]. Power plants can incur stiff penalties if they are found in

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This thesis follows the style of Fuel.

violation of the standards. In order to comply with the NO_x standards, new technologies must be developed and utilized to reduce the NO_x levels. [6]

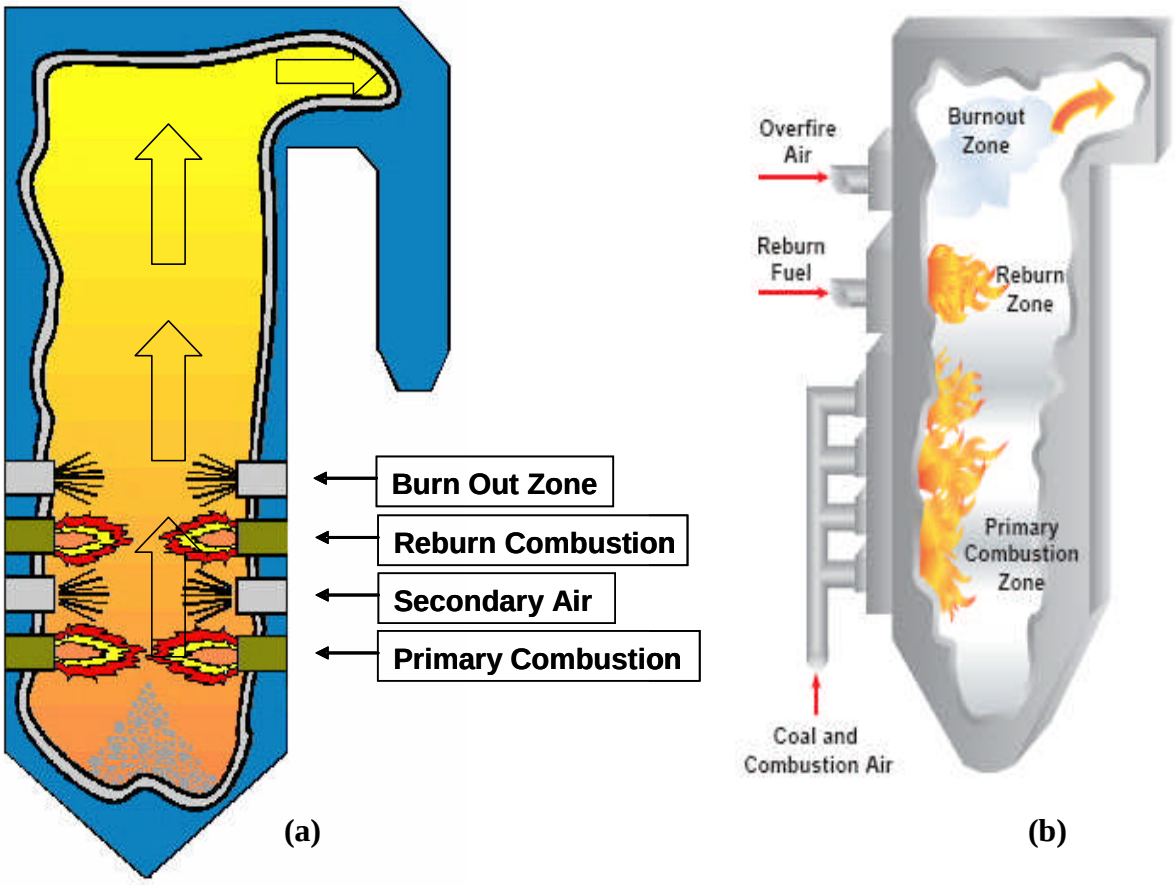

Figure 1: Schematic of (a) a modern coal fired burner with air staging and reburn zone and (b) a conventional coal fired burner and reburn zone

In a conventional coal burner (Figure 1b) coal is mixed with air called transport air (almost 15-20 %) while the remainder (swirl air) is preheated to about 500 K and supplied with swirl injectors to better mix the air and pulverized coal. In a modern coal

burner (Figure 1a), air staging is adopted; the air in primary burner is generally only 70 to 90 % of the total air required for complete combustion. Each burner still splits the air as transport and swirl air. The remaining air (10-30%) required for complete combustion is supplied through secondary air ports. After the secondary air (Figure 1a) or after primary combustion zone (Figure 1b), there is often a reburn combustion zone. The reburn zone is a fuel rich zone whose primary purpose is NO_x reduction. Natural gas is the most common reburn fuel used today. Firing natural gas in the reburn zone will generally reduce the total NO_x emissions by 50%-65%. The fuel rich combustion found in the reburn zone produces hydrocarbon fragments which react with N_2 and subsequently with NO to form N_2. In order to reduce costs of natural gas as reburn fuel, attempts have been made to fire coal in the reburn zone, but these attempts have not been able to achieve the same level of NO_x reduction as those obtained with natural gas.

The current research at Texas A&M University concentrates on firing cattle manure collected from feedlots or feedlot biomass (FB) as a reburn fuel. This reburn technology has the potential to be a cost effective method for reducing NO_x levels in power plants near cattle feedlots.

Past research has not established which operating conditions work best for NO_x reduction using FB as a reburn fuel. In order to know how much biomass is needed and to establish guidelines for optimal NO_x reduction, further research is necessary. This research is expected to yield the best operating conditions for optimal NO_x reduction. [7-8]

LITERATURE REVIEW

The literature review is a discussion of research that has been conducted with regard to NO_x formation and reduction. First, the mechanisms by which NO_x is formed and reduced are discussed. Also, the different applied techniques of NO_x reduction are discussed. Finally, the use of biomass as a reburn fuel is discussed. This brief discussion of NO_x formation and reduction helps contextualize the current research.

NO_x Formation Mechanisms in Coal and Biomass Combustion

During the combustion of hydrocarbons in air, nitrogen oxides form. NO_x produced in a reactor depends on many factors, including: the type of fuel, the amount of oxygen available, and the temperature of the flame. The three most common mechanisms for NO_x formation are fuel NO_x, thermal NO_x, and prompt NO_x. Thermal NO_x is formed from nitrogen in the air oxidizing at high temperatures. Fuel NO_x is formed from the oxidation of nitrogen found in the fuel. Prompt NO_x is formed during fuel rich combustion when hydrogen cyanide (HCN) oxidizes to form NO.

Extensive research has been done to better understand the mechanisms governing NO_x formation in pulverized coal. Little research has been completed in the area of NO_x formation in biomass. The chemical and physical principals governing formation of NO_x in coal should also apply to biomass. Some of the mechanisms governing the formation of NO_x during coal combustion are well understood such as thermal NO_x and Prompt NO_x. Another important mechanism that has proven more difficult to understand and

model is fuel NO_x. Also, the effect of devolatilization and char burn-out on NO_x levels is very difficult to model.

Thermal NO_x is formed at elevated temperatures when nitrogen in atmospheric air oxidizes to form NO. Levels of thermal NO_x can be computed using the extended Zeldovich Mechanism. This mechanism includes three principal reactions:

$$O + N_2 \leftrightarrow NO + N_2$$
$$N + O_2 \leftrightarrow NO + O_2 \quad (1)$$
$$N + OH \leftrightarrow NO + H \ .$$

These reactions can quite accurately predict the thermal NO_x formation using finite kinetics. [9]

Prompt NO_x is another NO_x formation mechanism that occurs in fuel rich environments. It is termed prompt NO_x because it forms very quickly near the flame zone. During rich combustion, fuel fragmentation causes several species such as CH, CH_2, C, C_2 and C_2H to form. These compounds then react with atmospheric nitrogen to form nitrogen species which react with oxygen to form NO. [9]

Fuel NO_x is created from nitrogen in the fuel. This nitrogen evolves from the fuel in the form of HCN, NH_3, and NH_2. These compounds then oxidize to produce NO. Only a fraction of the nitrogen in the fuel is converted to NO_x. The primary factors that affect the level of fuel NO_x generated include stoichiometry and flame temperature. [10]

Devolatilization of a coal or biomass particle is the release of volatile compounds from the fuel. This pyrolysis process occurs after a fuel is injected into a furnace. Then, the released volatiles, which include CO, CO_2, CH_4, C_2H_6, HCN, NH_3 etc., undergo

rapid gas phase combustion. After devolatilization, char burnout is the process by which the remaining carbon in coal is burned. Typically, the nitrogen compounds released during devolatilization create a large percentage of the total NO_x emitted from a reactor. With the advent of new low NO_x burners, the level NO_x formed from volatile nitrogen compounds has been greatly reduced. When low NO_x burners are used, it is reported that as much as 80% of the NO released comes from char-nitrogen[11]. For both devolatilization and char burnout, it is difficult to know and model what is happening inside and very near the coal particles and therefore difficult to apply NO_x formation mechanisms to the process. The modeling of nitrogen evolution and NO_x formation for coal particles is difficult due to the complexity of the coal structure, the heating rates effect on pyrolysis, and the transient conditions that are present. Currently research is being conducted to develop a reasonable model for devolatilization and char burnout. With faster computers continuously being developed, these complex phenomena can be more accurately modeled. [10]

Another new high temperature pathway has been proposed where NNH reacts with oxygen atoms to form NNHO and then decomposes into NH and NO. This mechanism becomes very important for temperatures above 1800K. The majority of coal fired utilities operate below this temperature and thus the effect of this mechanism is expected to be low. [12]

NO_x Reduction Techniques

The two main focus areas for controlling NO_x emissions are combustion modifications and exhaust gas treatment. Low-NO_x or staged burners, where air is introduced in stages to reduce the oxygen availability to fuel nitrogen compounds, and reburn combustion with overfire air are considered combustion modifications. Exhaust gas treatment methods or post combustion treatments include selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR).

SCR reduction methods use urea injection but with catalysts ; it generally reduce NO_x levels effectively at lower flue gas temperatures, but they generally require expensive catalysts and have other high operating costs. These factors cause many utilities to seek other less expensive methods for achieving NO_x reduction.

There are three common types of SNCR technologies being used today. Injecting ammonia (NH_3) into the exhaust stream is the oldest, most studied SNCR technology. The ammonia then decomposes and reacts readily with the NO_x to form H_2O and N_2. This process works over a temperature range of between 1100 and 1400 K[9]. Ather SNCR technology requires the injection of urea (NH_2CONH_2) or cyanuric acid ($(HOCN)_3$) into the exhaust stream. The urea and cyanuric acid decompose and react with NO similar to the ammonia [13].

Low-NO_x burners make use of rich combustion and a lower flame temperature to reduce NO_x. The lower flame temperature is achieved by premixing the fuel with deficient air so that there is no high temperature front in the flame. Also, the combustion is staged so that not all of the heat is released in the same area thus lowering the high

temperatures of this zone. This technology has been implemented in approximately 70% of all US power plants. The NO_x reduction rates range from 30 to 70%. Currently ultra low-NO_x burners are being researched to determine if it is possible to further reduce NO_x levels with the burner configuration and with smaller coal particles. [14]

Reburn combustion is another type of staged combustion where a fuel rich zone after the primary combustion zone is used to control emissions. When natural gas is used as the reburn fuel, the fuel rich environment produces HCN and NH_3 which react with NO to form N_2 through the reverse prompt NO_x mechanism. Reburn also helps SNCR methods achieve greater NO_x reduction by expanding the temperature window over which the reduction occurs. This window is larger for higher concentrations of CO, which are present after fuel rich reburn combustion. [15]

Often the main combustion environment is fuel rich. When this rich setup is used, overfire air is added to the burner after the main combustion zone in a zone called the burn out zone. This air is used to complete the combustion process and is generally on the order of 10 to 20% of the total air requirements. A rich primary combustion zone combined with overfire air has shown to reduce NO_x by 20 to 40%. This NO_x reduction occurs when the air in the primary firing zone is reduced to near or sub-stochiometric levels. The low oxygen levels inhibit the formation of NO_x. Systems using overfire air capabilities may have more problems with water wall corrosion caused by the higher levels of CO and H_2S generated during rich combustion. There is also generally a larger amount of unburned carbon in the fly ash because the residence time for char burnout is reduced. [16]

Another relatively new NO_x reduction technique, that only recently became feasible, uses oxygen and re-circulated exhaust gas as the oxidizer in the combustion zone. Enough exhaust gas is re-circulated to achieve a near 20% oxygen level prior to combustion. This concentration of oxygen is required to maintain the temperature at an acceptable level. This type of combustion scheme has been reported to reduce NO_x levels by 75% compared to the emissions from air fired combustors. [17]

Other Factors That Affect NO_x

Several other factors also affect the levels of NO_x in a coal combustor. Coal properties have a large influence on the NO_x generated during the combustion process. These properties include the nitrogen content, the makeup of the mineral matter, and the size of the coal particles.

As stated in the section on NO_x formation mechanisms, NO_x generated from nitrogen in the fuel is a major source for NO. As would be expected, fuels that have less nitrogen content emit less fuel NO_x. The fuel NO_x is not solely dependent on the amount of nitrogen in the fuel. The stoichiometry and flame temperature are also factors that affect the levels of fuel NO_x. [10]

The mineral matter in coal can also affect the NO_x emissions. Researchers have shown that calcium (Ca) in coal leads to more NO_x while sodium (Na) in coal ash aids in reducing NO_x levels [18]. The calcium forms compounds with nitrogen that cause a greater percentage of the fuel nitrogen to form NO. Sodium has a strong catalytic effect in the reduction of NO to N_2 by aiding the N+O and char reaction [19]. Iron in the coal

also has a NO_x reducing property by catalytically aiding the reaction of NO with CO to produce CO_2 and N_2 [19].

When larger coal particle sizes are burned, it requires more time for them to combust and a longer residence time is needed. This causes the oxygen concentration in the combustion zone to increase and therefore leads to more NO_x generation since NO_x forms easiest under fuel lean conditions. Keeping the size of the coal particles as small as possible helps lower emissions and reduces the amount of unburned carbon in the fly ash. [20]

Biomass Combustion and NO_x Reduction

Much research has been done in the area of biomass combustion as a technology to reduce coal consumption, lower emissions, and dispose of biomass. The use of biomass for combustion is favorable to utilities and scientists because it is a CO_2 neutral fuel. CO_2 neutral fuels are generally derived from plant material which absorbs CO_2 during photosynthesis and then releases the CO_2 back into the environment when combusted. Common biomass fuels used include wood, straw, animal waste, sugarcane residue, olive residue, sewage sludge, and municipal solid waste.

When co-firing pine sawdust with coal, it was found that NO_x levels and unburned carbon in the fly ash increased when the same grinder was used to pulverize the coal and sawdust. This increase was attributed to larger coal particle sizes and the moisture in the wood causing a delay in the ignition of the coal and biomass. It is

recommended that separate coal and biomass grinders and separate feeding systems be used to ensure that the biomass does not cause the coal grinders to perform poorly. [20]

Another research group determined that it should be possible to achieve 45% NO_x reduction (essentially due to low N in saw dust) using sawdust as a reburn fuel with air as the carrier gas. A 55% reduction is possible when using re-circulated flue gas as the carrier. This level of reduction was achieved under only the best mixing setup, opposed fired reburn injectors and overfire air injectors. They report that their results are consistent with other results showing a 60% reduction in NO_x. [21]

Municipal solid waste (MSW) is another biomass commonly combusted. It is reported by Patumsawad [22] that MSW can be co-fired with coal in fluidized bed combustors. He reports that the high ash content of the MSW reduces the combustion efficiency approximately 12% when firing 20% MSW by mass. It was also reported that there was less SO_2 emissions because of the low S content of the MSW and more CO emissions caused by a lower bed temperature.

In Germany, Hein and Spliethoff [23] did considerable research with sewage sludge, straw, and Miscanthus Sinensis, a feedstock. They found that each of these biomasses reduce NO_x emissions when they are used as reburn fuels in coal fired plants. For large particle sizes, a long residence time was needed to completely burn the biomass. The Miscanthus and straw also reduced the SO_2 emissions due to their low levels of sulfur. SO_2 emissions rose for the sewage sludge because there was a higher level of sulfur in the sludge than in the coals used.

Also in Germany, Hartmann and Kaltschmitt [24] found that firing 10% straw or residual wood in an existing power plant reduces all investigated emissions. The straw reduced the emissions of NO_x and SO_2 by approximately 46% and 80% respectively. The residual wood had even better results with NO_x and SO_2 reduction of 66% and 95% respectively. These measurements were taken after desulphurization and denitrofication treatments were performed. They concluded that the use of biomass for co-combustion is beneficial to the environment as compared to using only coal.

Annamalai et al. [7] used cattle feedlot biomass for co-firing. They found that the co-firing 10% biomass reduced NO_x emissions by about 10 %, but the CO emissions increased. They suggest that the higher volatile matter in the feedlot biomass depletes the oxygen rapidly, which inhibits NO_x formation. Also, it may be possible that the nitrogen in the fuel is released as NH_3, which reacts with NO_x to create N_2. Further, it was reported that co-firing 20% biomass reduced NO_x even more. It is not clear whether stoichiometry or some other effect caused the NO_x reduction.

In further research under the direction of Annamalai [8], it was found that using feedlot biomass as a reburn fuel could reduce NO_x by as much as 62% or five times greater than the reduction achieved with coal as the reburn fuel. He also found that a flat spray injector or an injector that has an ovule exit provided better NO_x reduction due to better mixing. The research shows found that firing cattle feedlot biomass in the reburn stage of a coal fired power plant can reduce NO_x emissions by as much as eighty percent under certain conditions [25].

These reburn experiments were conducted with FB and Wyoming subbituminous coal. These experiments focused on what type of injector would provide the greatest level of NO_x reduction. The experiments showed that injectors that decrease the mixing time and increase the residence time in the reburn zone give better NO_x reduction. Since NO_x reduction data exists for Wyoming subbituminous coal, it will be used as a baseline to compare results. [8]

OBJECTIVES

The overall objective of the current research is to develop alternative energy conversion technologies for utilizing animal wastes or FB. One of the technologies is to use FB as a reburn fuel for reduction of NO_x. The current research will focus on investigating the levels of NO_x reduction obtained using FB as a reburn fuel and to determine the operating conditions for optimum NO_x reduction. In order to complete this NO_x reduction study, the following tasks need to be performed.: 1. Acquire the required amounts of pulverized biomass and coal. 2. Determine the physical and chemical properties of the fuels. 3. Modify the current burner facility for reburn experiments with 0° (lateral) and 45° injectors. 4. Investigate the effects of using different FB fuels for reburn. The reburn fuels used in this research include high-ash partially composted feedlot biomass (HA PC FB), low-ash partially composted feedlot biomass (LA PC FB), and mixtures of FB with Texas lignite coal. 5. Study the effect of the reburn fuel injection angle by using 0° or lateral and 45° injection angles. 6. Inject the reburn fuel with pure air and simulated vitiated air. 7. Report the levels of NO_x in the exhaust gases of the burner measured with a combustion gas analyzer. 8. Summarize the conclusions on feedlot biomass as a reburn fuel in power plants firing Texas lignite coal.

By executing these tasks, the operating conditions that gave the best NO_x reduction are identified. The results from the current experiments provide guidelines for coal fired utilities to fire feedlot biomass in their boilers to reduce NO_x.

The use of feedlot biomass also relieves the cattle industry of the excess manure, which can itself cause adverse effects on the environment. By developing this technology, coal fired utilities can meet the NO_x emissions requirements and also help the cattle industry dispose of their excess manure.

EXPERIMENTAL FACILITY

The reburn furnace consists of a 15.24 cm (6 in) diameter, 182.88 cm (6 ft) long downward fired combustor (Figure 3). The main burner at the top burns natural gas and the reburn zone is equipped with an injection setup for solid fuels. The furnace is made with a steel frame containing a two inch layer of insulation and a two inch section of refractory.

Along the walls of the furnace are several gas sampling ports and temperature measurements ports. There are also three wall temperature measurement locations. Water jets are used to cool the hot exhaust gasses before they enter the exhaust system.

Because the furnace operates at a relatively low temperature, NO_x is generated with ammonia. The ammonia is injected with the primary fuel and is converted to NO_x during combustion. The flow of ammonia also allows for the control of NO_x levels.

The primary air for the main burner is supplied from a large blower (Figure 3). After leaving the blower, the air is heated in an air pre-heater to between 29 and 93 °C (85 and 200 °F) before entering the furnace. The pre-heat temperature is varied to better control of the maximum furnace temperature.

The natural gas for the main burner is supplied from the standard natural gas lines in the lab. The flow rate of natural gas is controlled with a digital flow meter and controller. A feeder and venturi system entrains the solid reburn fuel in air and the mixture is blown into the furnace 45.72 cm (18 in) below the main burner. The reburn fuel is injected into the burner laterally or at a 45° angle. The 45° injection angle is used

to increase the residence time of the reburn fuel and to give time for more NO_x reduction. Figure 2 shows how each injection scheme will work.

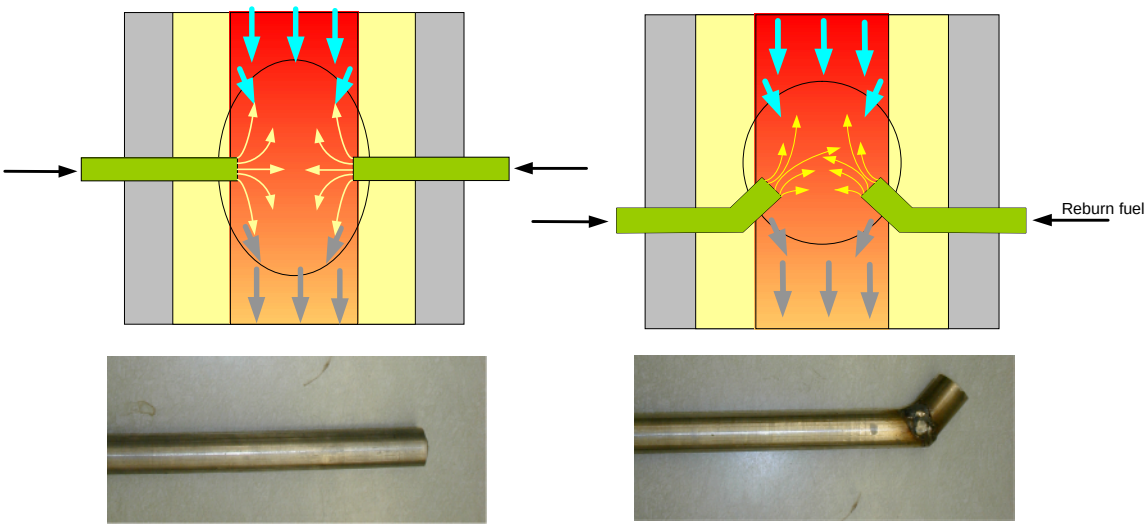

Figure 2: Schematic and images of 0° (lateral) and 45° reburn fuel injection scheme and injectors

The furnace is operated at a slightly negative pressure. The negative pressure ensures that no exhaust gasses are emitted into the laboratory and it also ensures that all flames are maintained within the furnace. The vacuum is maintained with an exhaust fan and a damper on the exhaust line. The fan operates continuously and the damper is adjusted to maintain a vacuum pressure of approximately 0.25 cm (0.1 in) of water.

A schematic of the reburn setup is shown in Figure 3. The diagram contains all of the major components of the setup that will be used to conduct the research experiments.

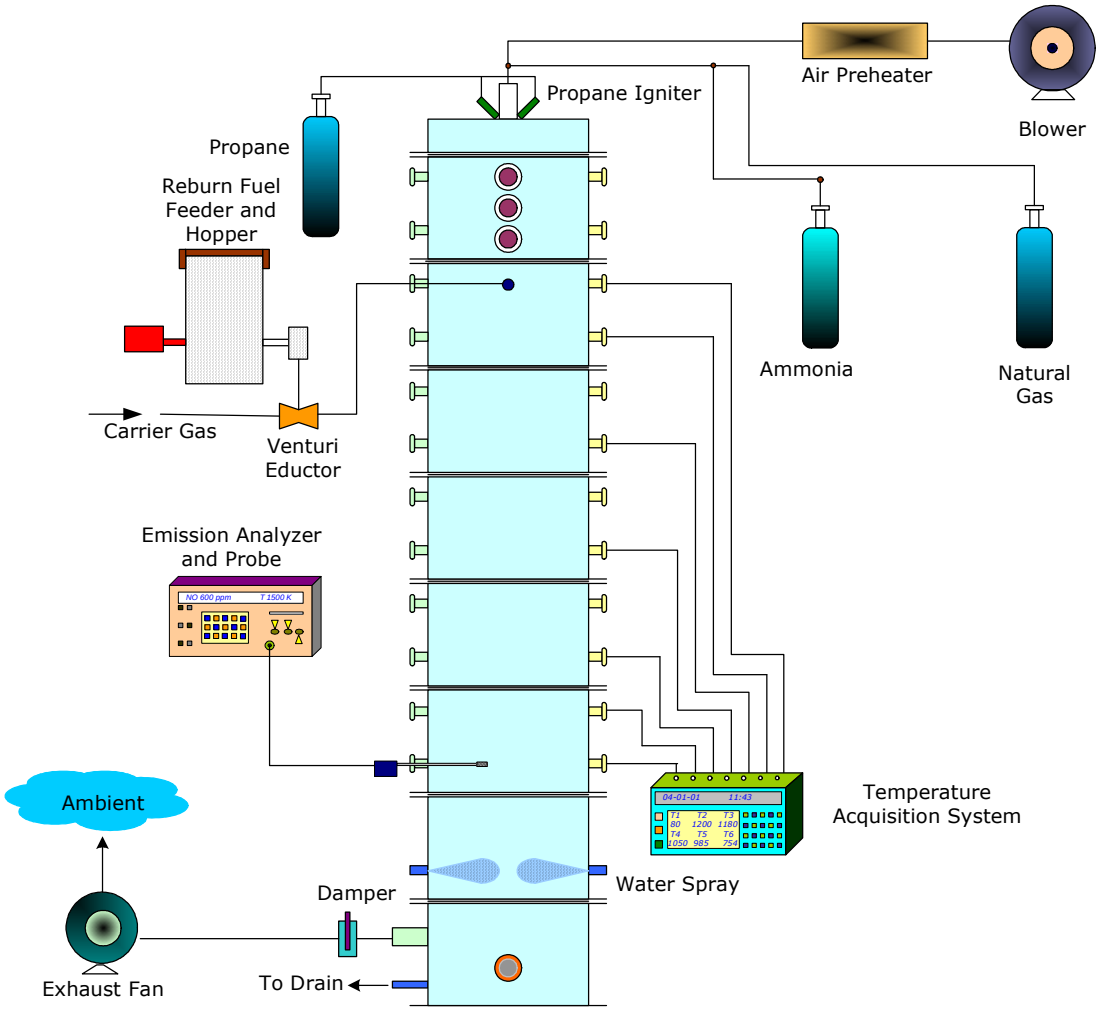

Figure 3: Schematic of Renewable Energy Lab furnace equipped for reburn experiments

PROCEDURE

As established in the literature review, the stoichiometry of the reburn zone has a large effect on the level of NO_x reduction achieved in the combustion and reburn zone. For this reason, each reburn fuel and fuel blend was fired for equivalence ratios from 1.00 to 1.15 in increments of 0.05. The equivalence ratio was varied by varying the motive airflow for the reburn fuel. The use of vitiated air in the reburn zone has also been reported to reduce NO_x. It is difficult to re-circulate exhaust gases with the reactor used in this study; therefore the oxygen concentration of the motive air was reduced with nitrogen gas in an effort to simulate vitiated air.

The reburn zone temperature for the experiments was held between 1120 and 1230 °C (2050 to 2250 °F). In order to ensure that the furnace was near steady state and that temperature changes during the experiment would not affect the data, each operating condition was set and maintained until all reactor temperatures were near steady state. After the temperatures were steady, the emission gas analyzer was used to determine NO_x levels.

Each measurement consisted of several parameters including combustion gas temperature measurements in the following locations: at the reburn zone, 15.24 cm (6 in) below the reburn zone, 30.5 cm (12 in) below the reburn zone, 45.72 cm (18 in) below the reburn zone, 76.2 cm (30 in) below the reburn zone, and 137.16 cm (54 in) below the reburn zone. Wall temperature measurements were measured at 45.72 cm (18 in) below the reburn zone, 91.44 cm (36 in) below the reburn zone, and 137.16 cm (54 in) below the reburn zone. In order to determine the level of NO_x and excess oxygen present in the

gas stream before the reburn zone, gas composition measurements were conducted before the reburn fuel was injected. After the level of NO_x was determined and the primary zone equivalence ratio was at the desired level, the reburn fuel was fired. The levels of O_2, NO_x, CO, CO_2, and combustibles (C_xH_y) were then measured 137.16 cm (54 in) below the reburn zone. After the measurements were taken, the reburn fuel was shut off and a check was done to ensure that the level of NO_x generation was still consistent with the initial setting. This process was followed for each measurement. For a more detailed description of how each experiment was conducted, see Appendix B.

RESULTS AND DISCUSSION

The results and discussion section discusses the fuels used for the research conducted as well as the properties of these fuels. The operating conditions found in the reactor including temperatures and gas composition are also discussed. The NO_x measurements are presented and discussed for all experiments. The effect of changing the operating conditions on NO_x emission levels is also presented. Finally, a few other observations noted while conducting the research are presented.

Primary Fuel

Natural gas was fired in the primary combustion zone for all experiments. There was very little change in the composition of the natural gas. The average fuel composition was 96% methane. All other components of the fuel were in small quantities and were considered negligible. For all calculations performed for the current research, the total fuel composition was assumed to be methane.

Reburn Fuels

Several fuels and fuel blends were used as reburn fuels. The fuels consisted of low-ash partially composed feedlot biomass (LA PC FB), high-ash partially composted feedlot biomass (HA PC FB), Texas Lignite Coal (TXL), Wyoming Subbituminous coal (WYC), and blends of FB and TXL. Each of the fuels used and their respective ultimate and proximate analyses are listed in Table 2.

All of the biomass used for this project were collected and prepared at the Texas Engineering Experiment Station in Bushland, TX. The high-ash feedlot biomass was collected from feedlots with a soil surface and then composted in windrows for 55 days. The low-ash feedlot biomass was collected from feedlots paved with fly ash. It was also composted in windrows for 55 days. Less soil is collected with the manure gathered from paved feedlots and therefore less ash is in the fuel. After composting the biomass, it was dried and finely ground.

The reburn fuel blends consisted of 70% LA PC FB/30% TXL, 50% LA PC FB/50% TXL, 10% LA PC FB/90% TXL, 70% HA PC FB/30% TXL, 50% HA PC FB/50% TXL, and 10% HA PC FB/90% on a mass basis. The fuels were well mixed in five gallon buckets prior to being placed in the fuel hopper of the reburn feeding system.

The higher heating values of HA PC FB and LA PC FB on a mass basis are 5207 and 13267 kJ/kg (2239 and 5704 BTU/lb) respectively. On a dry ash free basis, the heating values for LA PC FB and HA PC FB are 17865 and 20733 kJ/kg (7681 and 8931 BTU/lb) respectively. The HHV of LA PC FB is 2.5 times larger than HA PC FB on an as received basis whereas it is only 1.2 times larger for the dry ash free case. Ash and moisture content are not the only differences; however, the data shows that a large percentage of the difference can be attributed to ash and moisture. For more fuel information on the fuel compositions, see Table 2.

Table 2: Average fuel compositions for all fuels in pure form

AVERAGE FUEL COMPOSITIONS								
	HA PC FB		LA PC FB		TXL		WYC	
Proximate (%)	As Rec.	Dry	As Rec.	Dry	As Rec.	Dry	As Rec.	Dry
Moisture	17.00	0.00	19.64	0.00	38.34	0.00	32.88	0.00
Ash	53.85	64.88	16.50	20.53	11.46	18.59	5.64	8.40
Volatiles	25.79	31.07	52.33	65.11	24.79	40.20	28.49	42.45
Fixed C	3.36	4.05	11.54	14.36	25.41	41.21	32.99	49.15
HHV (kJ/kg)	5207	6274	13267	16507	14289	23172	18196	27114
DAF HHV (kJ/kg)	17865		20773		28465		29599	
	HA PC FB		LA PC FB		TXL		WYC	
Ultimate (%)	As Rec.	Dry	As Rec.	Dry	As Rec.	Dry	As Rec.	Dry
Carbon	14.92	17.97	33.79	42.05	37.18	60.30	46.52	69.32
Hydrogen	1.39	1.68	3.65	4.55	2.12	3.44	2.73	4.06
Nitrogen	1.13	1.36	1.97	2.45	0.68	1.11	0.66	0.98
Oxygen	11.40	13.73	23.94	29.78	9.61	15.58	11.29	16.83
Sulfur	0.31	0.38	0.51	0.64	0.61	0.98	0.27	0.41
Ash	53.85	64.88	16.50	20.53	11.46	18.59	5.64	8.40
Moisture	17.00	0.00	19.64	0.00	38.34	0.00	32.88	0.00

The particle size distribution of the two fuels is quite interesting (Table 3). A larger percentage of very small particles is found in the high ash fuel. This may suggest that the ash tends to be the smaller particles and the combustibles are larger. If this is the case, a method for removing portions of the ash from the fuel could be developed with the use of a particle size separator. Theoretically, the smaller particle sizes would heat faster, release their volatiles faster and thus reduce NO_x more readily. The HA FB does the opposite. As will be shown later, the HA FB does not reduce NO_x as well as LA FB. This is further evidence to suggest that the small particles may be primarily ash. It is

also important to note that the soil in the Bushland, TX area is Pullman clay loam. The particle sizes for clay are <2 μm and the particle sizes for loam are from 2 to 50 μm.

Table 3: Fuel particle size distribution

Particle Size Distribution				
Mean Diameter (μm)	**HA PC FB** (%)	**LA PC FB** (%)	**TXL** (%)	**WYC** (%)
1596	0.01	0.05	0.01	0.0
1015	0.03	0.10	0.00	0.0
570	1.68	7.58	4.97	1.69
225	6.44	27.21	33.72	15.35
113	13.73	22.56	37.09	45.02
60	20.43	16.06	11.82	21.76
22.5	57.69	26.44	12.38	16.19
SMD	32.71	56.28	81.02	64.45

The composition of the ash was also determined. These results are presented in Table 4. These show that there is a higher percentage of silicon, aluminum, and calcium in the HA FB. These are likely to be in the soil found in the feedlots. It is also interesting to note that the chlorine concentration is much lower for the HA FB as compared to the LA FB. This may be because some of the chlorine leeches into the soil found below soil surfaced feedlots.

Table 4: Biomass ash composition

Ash Elemental Analysis (% mass)		
(Ash was calcined @ 1100 °F prior to analysis)		
	HA FB	LA FB
Silicon, SiO_2	64.68	25.55
Aluminum, Al_2O_3	7.72	1.94
Titanium, TiO_2	0.44	0.27
Iron, Fe_2O_3	2.90	1.37
Calcium, CaO	7.09	20.20
Magnesium, MgO	2.34	7.17
Sodium, Na_2O	1.38	4.94
Potassium, K_2O	4.50	12.70
Phosphorus, P_2O_5	2.81	11.11
Sulfur, SO_3	1.06	4.46
Chlorine, Cl	0.68	5.02
Carbon dioxide, CO_2	1.35	1.71
Total ash analysis	96.95	96.44
Metals in Ash, equal-weight-composite, mg/kg		
Arsenic	4.12	3.96
Barium	669	2,620
Cadmium	<1	2
Chromium	<20	20
Lead	20	20
Mercury	<0.01	<0.01
Selenium	<2	2
Silver	<2	<2
Total metals in ash	693.12	2,667.96

Reburn Experiments

Table 5 lists the experiments that were conducted for this study. Two injection angles were compared for two different oxygen concentrations. The 20.9 % oxygen concentration represents pure air. The 12.5 % oxygen concentration represents vitiated air. In these experiments, the oxygen concentration was reduced to 12.5% with N_2 gas in an effort to simulate exhaust gas recirculation. The equivalence ratio was also varied during each experiment.

Table 5: Reburn experiment matrix (All fuel percentages are mass %)

Experiment Matrix				
Experiment	**Reburn Fuel**	**Injection Angle**	**Equivalence Ratios**	**% O_2**
1	WYC	45°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
2	TXL	45°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
3	LA PC FB	45°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
4	HA PC FB	45°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
5	90% TXL/10% LA PC FB	45°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
6	90% TXL/10% HA PC FB	45°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
7	70% TXL/30% LA PC FB	45°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
8	70% TXL/30% HA PC FB	45°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
9	50% TXL/50% LA PC FB	45°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
10	50% TXL/50% HA PC FB	45°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
11	WYC	0°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
12	TXL	0°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
13	LA PC FB	0°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
14	HA PC FB	0°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
15	90% TXL/10% LA PC FB	0°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
16	90% TXL/10% HA PC FB	0°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
17	70% TXL/30% LA PC FB	0°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
18	70% TXL/30% HA PC FB	0°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
19	50% TXL/50% LA PC FB	0°	1.00, 1.05, 1.10, 1.15	20.9, 12.5
20	50% TXL/50% HA PC FB	0°	1.00, 1.05, 1.10, 1.15	20.9, 12.5

Using the higher heating value (HHV) of each fuel and fuel blend, the fuel flow required for the primary and reburn zone combustion were calculated. With the mass flow and the ultimate analysis of the fuel, the air requirements in the reburn combustion zone were calculated with Equation 2. [26]

$$CH_hN_nO_oS_s + \frac{\left(1 + h/4 + s - o/2\right)}{\phi}\left(O_2 + 3.76N_2\right) \rightarrow$$

$$cCO_2 + dCO + \left(\frac{h}{2}\right)H_2O + (s)SO_2 + eO_2 + \left[\frac{1}{\phi}\left(1 + \frac{h}{4} + s - \frac{o}{2}\right) + \frac{n}{2}\right]N_2$$

where

$$c = 1 - d$$

$$d = 0 \quad for \quad \phi \le 1 \quad and \quad \left(2c - o - 2 \cdot \frac{\left(1 + h/4 + s - o/2\right)}{\phi} + \frac{h}{2} + 2s\right) \quad for \quad \phi \ge 1$$

$$e = 0 \quad for \quad \phi \le 1 \quad and \quad e = \left(1 + \frac{h}{4} + s - \frac{o}{2}\right)\left(\frac{1}{\phi} - 1\right) \quad for \quad \phi \ge 1$$

(2)

In actual power plants, typically the main burner equivalence ratio (φ) is maintained at a level less than one. For the reburn zone, φ is generally kept at a level greater than one. For these experiments, φ in the primary zone was maintained at 0.95 and φ was varied from 1.00 to 1.15 in the reburn zone.

Equation 1 also provides an estimate for the levels of CO and SO_2 in the exhaust. The CO estimate may be a little higher than measured values since some unburned carbon is in the form of hydrocarbons. The estimate for SO_2 may also be high since some sulfur reacts to form SO_3, and some is left in the ash. These estimates will function as a guideline to ensure that the measured results are reasonable.

Operating Conditions

The total heat input for each experiment was set to 29.28 kW (100,000 BTU/hr). The primary combustion zone supplied 20.50 kW (70,000 BTU/hr) and the reburn zone

supplied 8.78 kW (30,000 BTU/hr). The primary zone combustion conditions were maintained the same for each experiment. These conditions were calculated with Equation 3. The fuel used was methane (CH_4). This equation also allows the control of NO_x emissions with the flow of ammonia. For the ammonia reaction, it is important to maintain a fuel-lean combustion zone or the ammonia may not react to form NO_x. The calculated conditions are detailed in Table 6.

$$C_x H_y + b \cdot (O_2 + A \cdot H_2O + B \cdot N_2) + c \cdot NH_3 \rightarrow CO_2 + b \cdot A \cdot H_2O + b \cdot B \cdot N_2 + d \cdot O_2 + c \cdot NO \quad (3)$$

Table 6: Primary combustion zone operating conditions

Primary Zone Heat Input	20.5 kW (70,000 BTU/hr)
Natural Gas Flow	30.1 SLPM (63.9 SCFH)
Primary Air Flow	320.3 SLPM (678.7 SCFH)
Ammonia Flow	0.123 SLPM (0.265 SCFH)
Equivalence Ratio	0.95

The heat input from the reburn zone was maintained at 8.78 kW (30,000 BTU/hr) for all experiments. The mass flow of the fuel changed for each experiment due to the variation of the heating value of each fuel. The equivalence ratio of the reburn zone was varied by changing the amount of air injected with the fuel. The vitiated air was simulated by diluting the oxygen concentration with nitrogen. Vitiation will increase the injection velocity because there is more mass and volume flow through the reburn injectors. The inside diameter of the reburn injectors was 1.27 cm (0.5 in). Typical operating conditions for a reburn experiment can be seen in Table 7.

Table 7: Reburn combustion zone operating conditions for 100% LA PC FB

Reburn Zone Heat Input	8.78 kW (30,000 BTU/hr)
LA PC FB Flow	39.8 g/min (5.26 lb/hr)
Reburn Air Flow (varies with φ)	99.1 to 116.6 SLPM (210 to 247 SCFH)
Nitrogen Flow (for vitiated only, varies with φ)	75.5 to 86.8 SLPM (160 to 184 SCFH)
Equivalence Ratios (φ)	1.0, 1.05, 1.10, 1.15
Fuel Injection Angle	0° and 45°
Injection Velocity for Vitiated cases (varies with φ)	23.0 to 26.8 m/s (75.5 to 87.9 ft/s)
Injection Velocity for Non-vitiated cases (varies with φ)	13.0 to 15.3 m/s (42.7 to 50.2 ft/s)

Ammonia Slip

Ammonia can be used to both generate and reduce NO_x. If ammonia is present in an oxygen-rich environment, NO will be formed, but if the ammonia is in an oxygen deficient environment, it will react with the NO that is present and form N_2. In order to ensure that ammonia that was injected in the primary zone to generate NO_x was all converted to NO, the levels of NO_x were measured before ammonia was injected and after ammonia was injected. The results from these measurements show that after the primary combustion zone, the levels of NO without any ammonia injection are between 50 and 100 ppm. After the ammonia is injected, the level of NO is between 400 and 420 ppm. This suggests that the ammonia is responsible for generating between 300 and 370 ppm of NO. The theoretical amount of ammonia required to generate 300 ppm NO is 1.49 cm^3/s (0.19 SCFH). The average amount of ammonia injected into the system was 1.34 cm^3/s (0.17 SCFH). This suggests that there is little or no ammonia slip or no ammonia from the primary zone being used to reduce NO_x further down the reactor. All ammonia in the primary zone is converted into NO. The difference in the theoretical

amount required and the amount injected may be attributed to measurement error or other errors inherent in the system.

Injection Angle Effects

Intuition says that a 45° opposed flow fuel injection system provides more residence and reaction time around the reburn zone when compared to a lateral injection of fuel. With a longer residence and reaction time, more NO_x reduction is possible. Appendix F includes some mixing time calculations for the reactor during hot flow. These calculations give an estimate of the mixing time for the lateral injection of 0.32 s when a linear mixing model is used with a mixing length of 30.48 cm (12 in).

The experimental data showed a greater variation between the levels of NO_x reduction with the 45° injection angle when non-vitiated air was used as compared to the reductions obtained when vitiated air was used. If you take the average reduction of NO_x for all fuels, the 45° injections has a 4.3% greater reduction compared to the 0° (lateral) injection for vitiated reburn air. However, the non-vitiated reburn average has a 13.5% difference in reduction. This difference could be caused by several factors. NO_x reduction with vitiated air works on the same principal as the 45° injection to reduce NO_x. The vitiated air reduces oxygen concentration by dilution while better mixing reduces oxygen concentration by mixing it with the oxygen depleted main combustion stream. Better mixing also causes the fuel to combust faster and thus reduces the oxygen levels. The reduced oxygen levels inhibit the NO_x formation mechanisms. The slight differences in the temperature profiles may also contribute to the difference in the

reduction rates between the 45° and 0° reduction schemes. The 45° injection scheme has slightly higher temperatures in the reburn zone. Higher temperatures should give rise to better NO_x reduction.

An observation made after conducting the 45° injection tests, found that there was a large amount of slag or melted ash buildup in the furnace just above the injectors. This ash buildup may have affected the 45° injection stream so that it was deflected in some way. Also, due to the restriction in the diameter of the reactor, the stream of gas from the primary zone was moving faster. It is unknown if the mixing patterns were disturbed and if they were disturbed, it is not known how this affected the data. For further discussion of this slag buildup, see the results section on other observations.

Temperature Profile of the Reactor

The temperature profile for each experiment is important because the reaction rates for the NO_x reduction reactions are very sensitive to temperature. For each experiment, the temperature profile was measured using K-type thermocouples. The

profiles all look very similar; however, there was some variation in the temperatures measured. Typical temperature profiles can be seen in Figure 4. For all cases, the temperature for the vitiated case was slightly lower than the temperature for the non-vitiated case. This lower temperature is expected since some heat is required to heat the added nitrogen. On average, the temperature profile was 17 °C (30 °F) lower for the vitiated case as compared to the non-vitiated case.

There was also a difference in the temperature profiles for the lateral versus 45° injection setups. There is a steeper drop in temperature at the reburn zone for the 0° injection as compared to the 45° injection (Figures 4 and 5). This may suggest that for the 45° injection combustion occurs more quickly and gives rise to hotter temperatures just after the reburn zone. Another possible explanation could be the fouling discussed in the section about other observations. The higher temperatures found with the 45° injection scheme should reduce NO_x levels better since the NO_x reduction reactions are highly dependent upon temperature. For figures including all temperature profiles, see Appendix H.

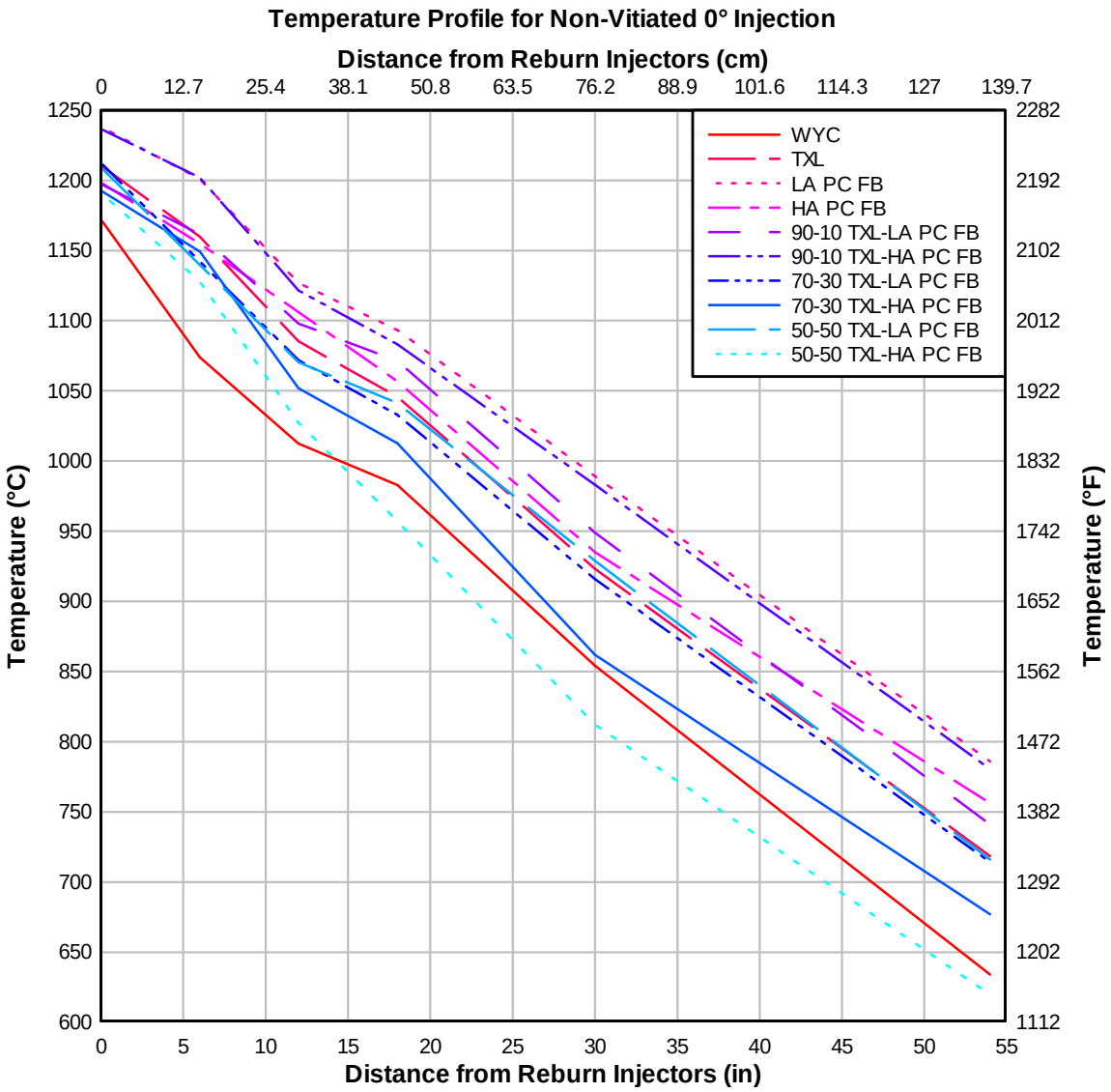

Figure 4: Temperature profiles for the 0° injection angle, non-vitiated experiments

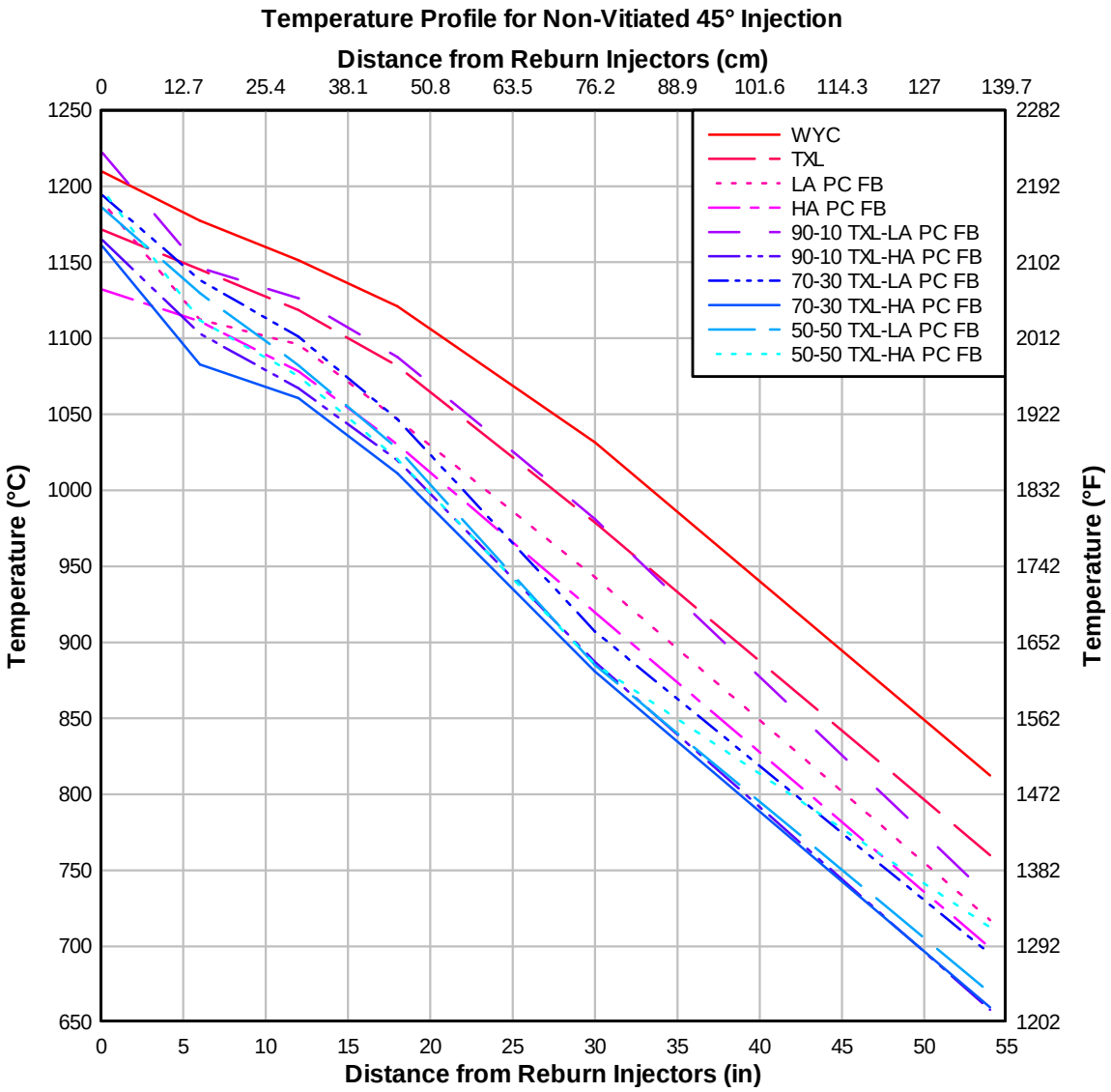

Figure 5: Temperature profiles for the 45° injection angle, non-vitiated experiments

Base Case Results

WYC was used for the base case in this research (Figure 6). It was used because past research had been conducted with this type of coal. The level of NO_x reduction achieved with WYC was similar to that found in past research. The past research found a reduction of between 6 and 10 % for a lateral injection. The base case for the current research achieved between 13 and 32 % reduction. One possible explanation for the difference in the results is the particle size distribution. 70 % of the WYC used for past research was below 100 μm in diameter while for the current research, 83% of the WYC used was below 75 μm. As discussed in the literature review, smaller particle sizes generally give rise to lower NO_x levels.

TXL and LA PC FB are also an important fuels for the research conducted. For this reason, a plot of the base case fuel (WYC), TXL, and LA PC FB are included in Figure 6 for the vitiated and non-vitiated cases.

The NO_x measurement error for each experiment is presented on the graphs with vertical error bars. There is also error associated with the equivalence ratio presented. All equivalence ratios in the thesis have an error of +/- 0.023. This suggests that an equivalence ratio of 1.00 could actually be from 0.977 to 1.023. For more information on the error calculations, see Appendix I.

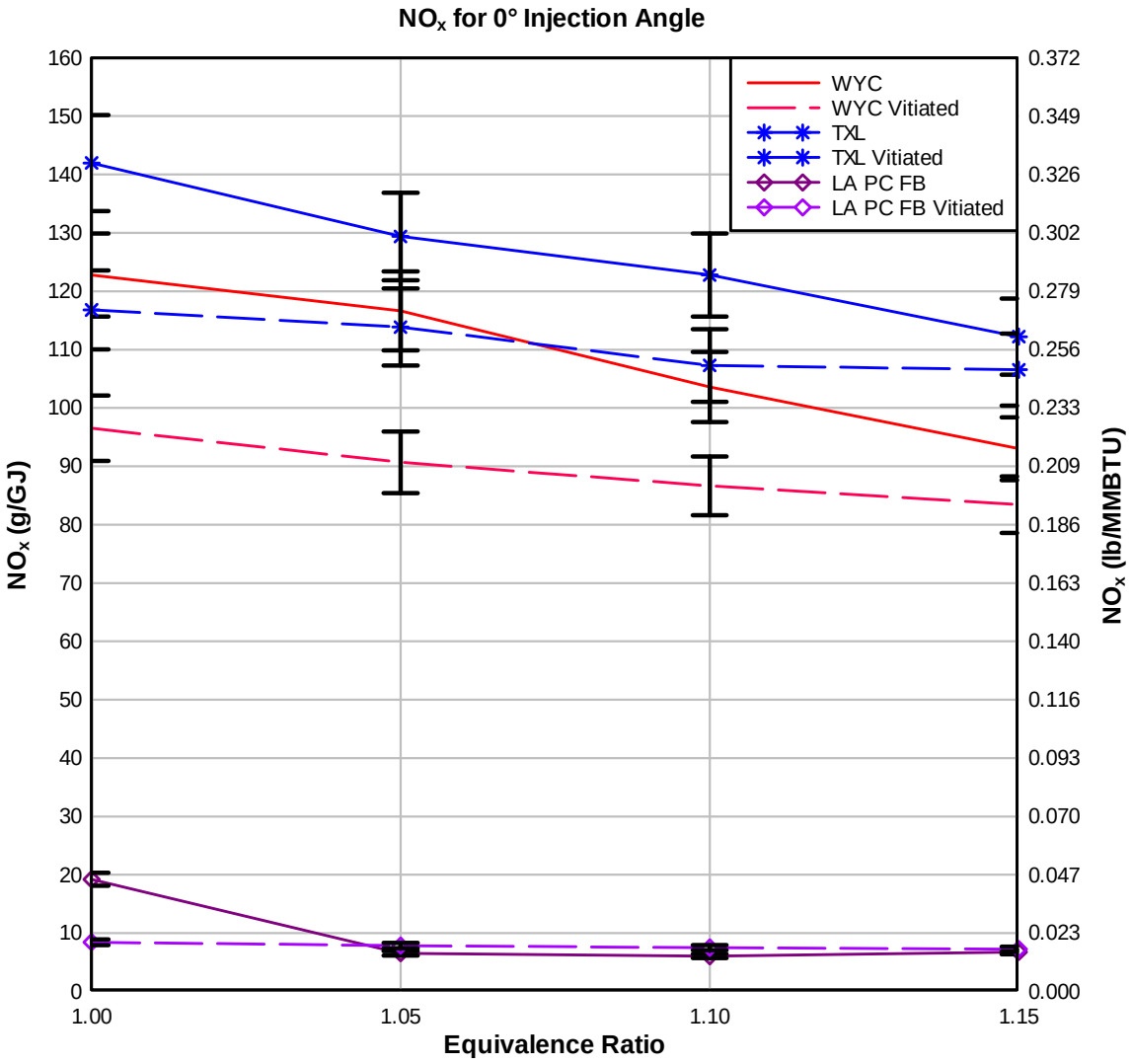

Figure 6: Base case fuel (WYC) compared to LA PC FB and WYC

Equivalence Ratio Effects

The greatest influence on levels of NO_x reduction was the equivalence ratio. In all experiments except for those for TXL injected at a 45° and with non-vitiated air, the level of NO_x reduction increased with increased equivalence ratio. The decrease in NO_x emission can be explained. With increased equivalence ratio, the oxygen in the combustion zone is depleted quickly. Low levels of oxygen slow down the NO formation reaction and allow the NO reduction reaction to be dominant in the combustion zone.

Figure 7 and 8 show the results from all experiments conducted with 0° and 45° injection angles respectively. The decreasing NO_x level with increasing equivalence ratio trend is evident in the observed data. Error bars were left off of this data because the purpose of the figure is to display the downward trend of NO_x level with increasing equivalence ratio.

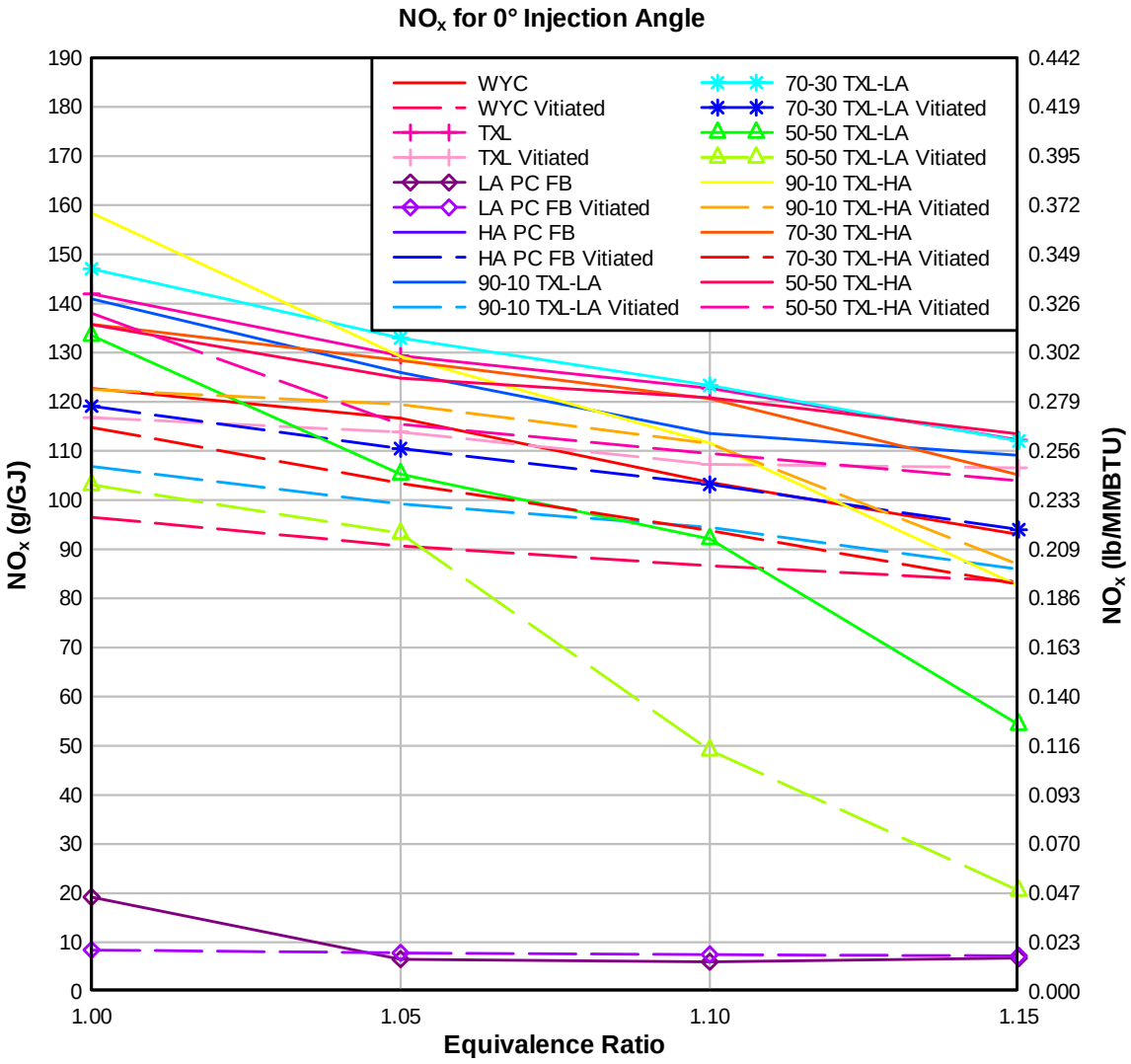

Figure 7: NO_x levels for FB and coal with a 0° injection angle

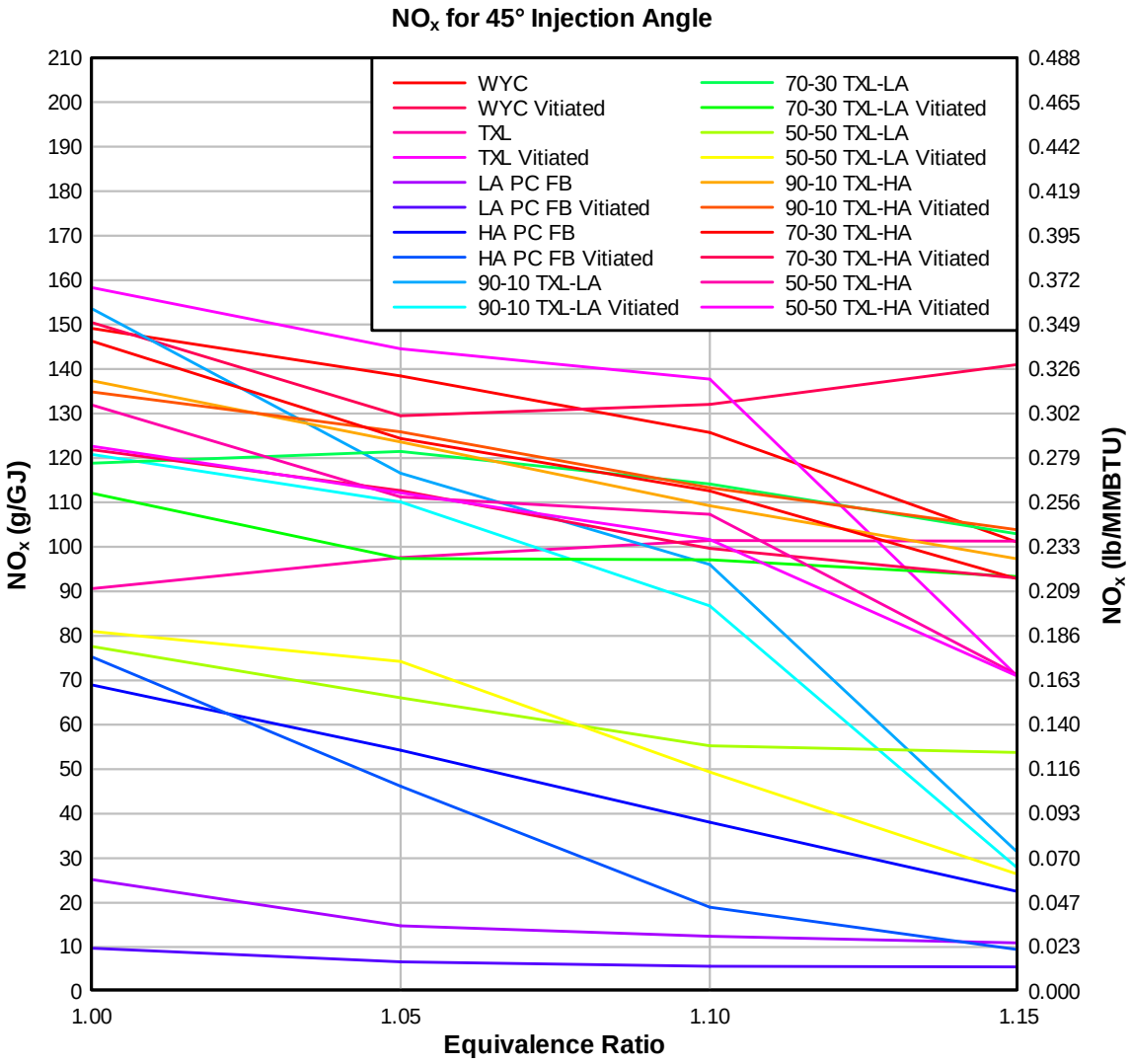

Figure 8: NO_x levels for FB and coal with a 45° injection angle

High Ash Biomass Compared to Low Ash Biomass

In all cases, better NO_x reduction was achieved with LA PC FB as compared to HA PC FB. On a dry, ash free basis, the ultimate analysis of the two biomasses is essentially the same. This leads one to consider what effect the ash may have. The lower NO_x reduction may be linked to the amount of heat required to heat the additional ash.

This would retard the release of the volatiles and thus slow down the oxidation of the volatiles. This could affect the rate of NO_x reduction and cause less NO_x to be reduced.

Another consideration is the catalytic or inhibiting effects of the ash. The effect of sodium and calcium was briefly discussed in the literature review. Based on the findings of the discussed study, sodium promotes NO_x reduction and calcium inhibits the reduction. The concentration of Na and Ca in the HA FB is less than that found in LA FB, but when fired, the mass flow of Na and Ca for HA FB and LA FB is the same for both fuels. The similarity is because the largest source for calcium and sodium in the manure is from the ration fed to the cattle. Since the mass flow is the same, it is assumed that the effect of the two metals is the same for both fuels. The composition of the ash is shown in Table 4 in the section on fuel composition.

The particle size distribution found in Table 3 indicates that there is a greater percentage of very small particles (< 60 μm) in the HA FB as compared to the LA FB. This may indicate that the particle size of ash is generally smaller than the particle size of combustible biomass. If this is the case, it may be possible to remove portions of the ash through screens, centrifugal, or other methods. The SMD is also shown in Table 3.

The difference in NO_x reduction levels for HA PC FB compared to LA PC FB can be seen in Figures 9. For both the vitiated and the non-vitiated cases, the LA PC FB reduced NO_x better when compared to HA PC FB.

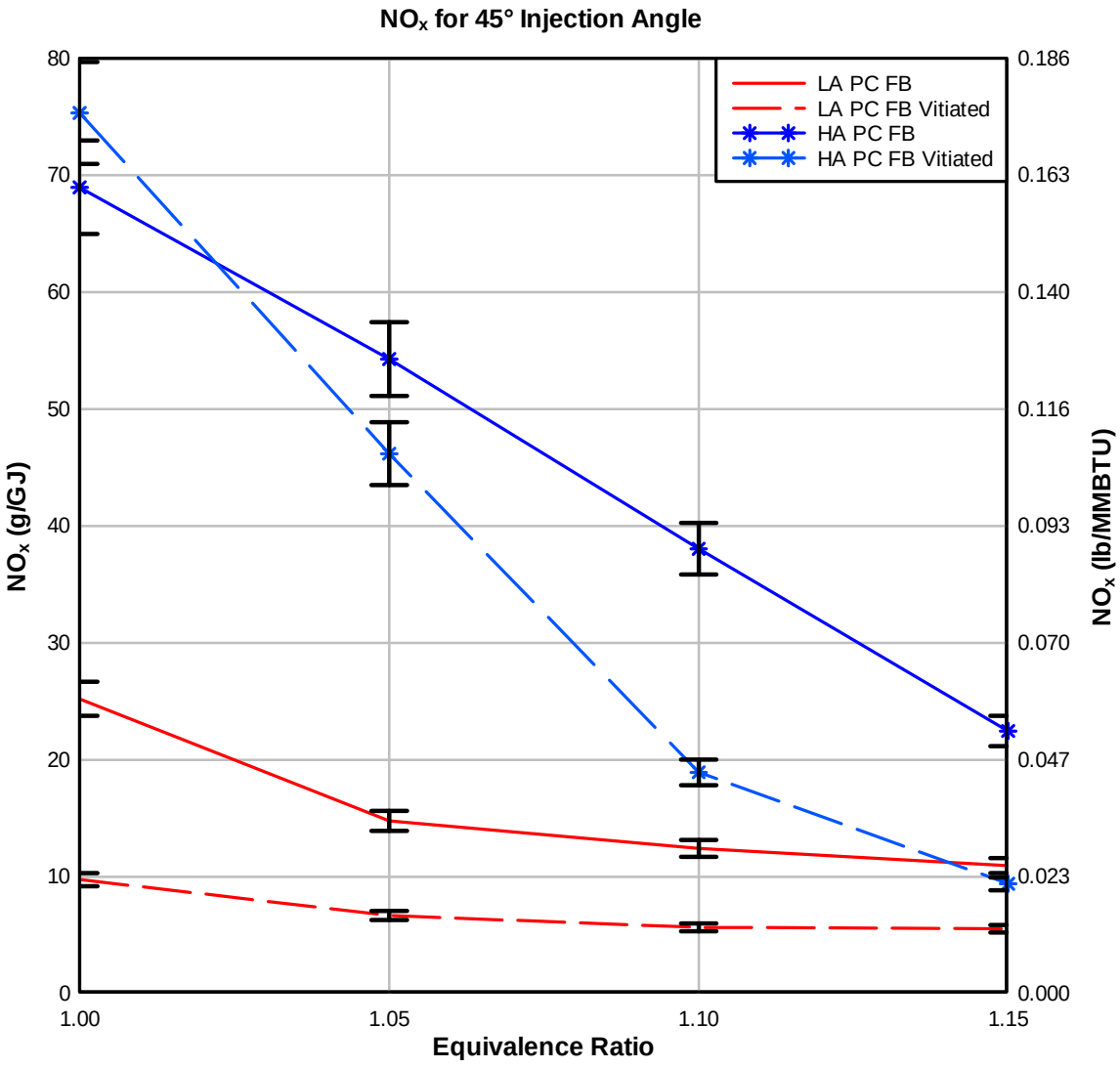

Figure 9: NO_x for HA PC FB compared to LA PC FB for both vitiated and non-vitiated reburn air

Fuel Blends

Blends of biomass and coal were used as reburn fuels to determine if fuel blends reduce NO_x levels as well as pure biomass. This section will discuss data obtained from the lateral injection of the fuel.

It was found that the average NO_x reduction obtained for 100% TXL was 11.0% and 20.9% for non-vitiated and vitiated reburn experiments respectively. For 100% LA PC FB, the level of NO_x reduction was 93.1% and 94.5% for non-vitiated and vitiated reburn experiments respectively. This shows that biomass is very effective in reducing NO_x. Table 8 includes each fuel blend with the level of NO_x reduction observed. It would seem logical that the level of NO_x reduction would increase with increased percentage of biomass. The results do not display this trend. It is difficult to discern whether an unknown phenomena is occurring or if the differences are a result of experimental error. It is recommended that more experiments be conducted to see if the results are consistent.

Table 8: Each fuel with its respective average level of NO_x reduction

Fuel/Fuel Blend	**% NO_x Reduction for 0° Injection Angle**	
	Non-Vitiated	**Vitiated**
WYC	22.5	36.5
TXL	11.0	20.9
LA PC FB	93.1	94.5
HA PC FB	Data Not Available	
90-10 TXL-LA	12.9	31.3
70-30 TXL-LA	8.3	24.1
50-50 TXL-LA	31.5	52.7
90-10 TXL-HA	14.3	21.7
70-30 TXL-HA	12.8	29.8
50-50 TXL-HA	12.0	17.0

If the results from further experiments correlate with those obtained in the present research, one possible explanation may be the following. For mixtures including only small percentages of biomass, the biomass may burn quickly and release all of the nitrogen species before the coal has time to burn and deplete the oxygen levels. This would create an environment where the ammonia released from the biomass is actually generating NO_x rather than reducing NO_x levels. Under this scenario, one would expect the NO_x levels to increase with small concentrations of biomass. After the concentration of biomass is high enough to lower the oxygen concentration to a level that inhibits NO_x formation, the levels of NO_x would decrease. To further illustrate this phenomenon, a plot of the percentage of NO_x reduction achieved versus the fuel blend is shown in Figure 10 for all experiments involving LA PC FB.

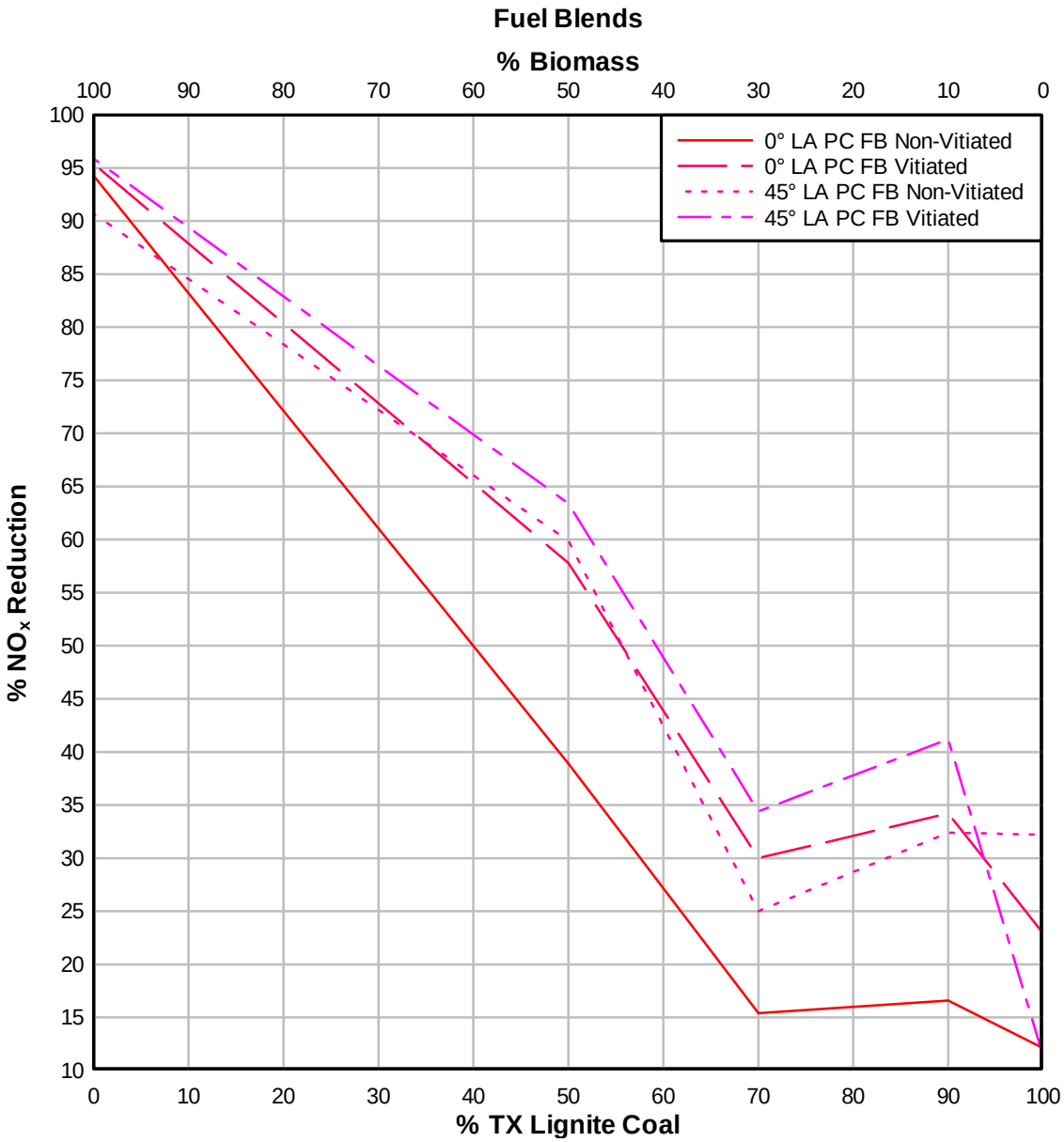

Figure 10: NO_x reduction for various fuel blends and firing schemes

Vitiated Reburn Air versus Non-vitiated Reburn Air

In actual power plants, re-circulated exhaust gas is often used as the motive air for the reburn fuel. There are two principal reasons why re-circulated exhaust gas

produces better NO_x reduction than using air alone. First, the low concentration of oxygen in the re-circulated gas causes the NO_x formation rate to be slower. Second, the low oxygen levels in the re-circulated exhaust gas create very rich regions near the fuel injection, before mixing is complete. This allows the nitrogen species to be released in an oxygen deprived region, thus allowing more HCN and NH_3 to be available for NO_x reduction rather than NO_x generation. The combination of these events reduces NO_x levels lower than those obtained through using purely air in the reburn zone. Another very small level of NOx reduction may occur because the re-circulated exhaust gas has some levels of NO_x. This allows for a small amount of NO_x to pass through the reduction region two times.

The experiments at hand attempted to simulate exhaust gas recirculation by injecting nitrogen gas with the reburn fuel motive air. The same amount of air was used; however, the oxygen concentration was lowered to 12.5 %. The simulated exhaust gas recirculation will not take into account the NO_x reduced due to recirculation, but it should account for the other, more dominant reduction modes.

When simulated vitiated air is used, the reduction in NO_x caused by dilution must also be taken into account when reporting the NO_x in parts per million (ppm) or on a volume basis. In these experiments, the levels of NO_x are reported on mass per heat output basis. This reporting method allows for better comparison of the results between the vitiated and non-vitiated cases. For more discussion on how the conversions from ppm to g/GJ, see Appendix G. Figure 11 compares the difference between non-vitiated and vitiated air. Another consideration that may be important is the specific heat of N_2 compared to CO_2. At a typical reburn zone temperature (1400 K or 2060 °F), the specific heat of nitrogen is 34.5 kJ/kmol-K while the specific heat of CO_2 is 57.7 kJ/kmol-K. When nitrogen gas is used to simulate vitiated air, there is no CO_2 in the exhaust. The actual CO_2 concentration of exhaust gas is around 12%. It is unknown whether the presence of the CO_2 in the exhaust gas has an effect on NO_x reduction.

When the average reduction of all vitiated cases are considered, the level of reduction caused by vitiation for lateral injection and 45° injection is 25.8% and 17.9% respectively. This shows that vitiation has a greater effect on the NO reduction when a lateral injection is used. This effect was discussed previously when the 45° injection angle effects on mixing were discussed.

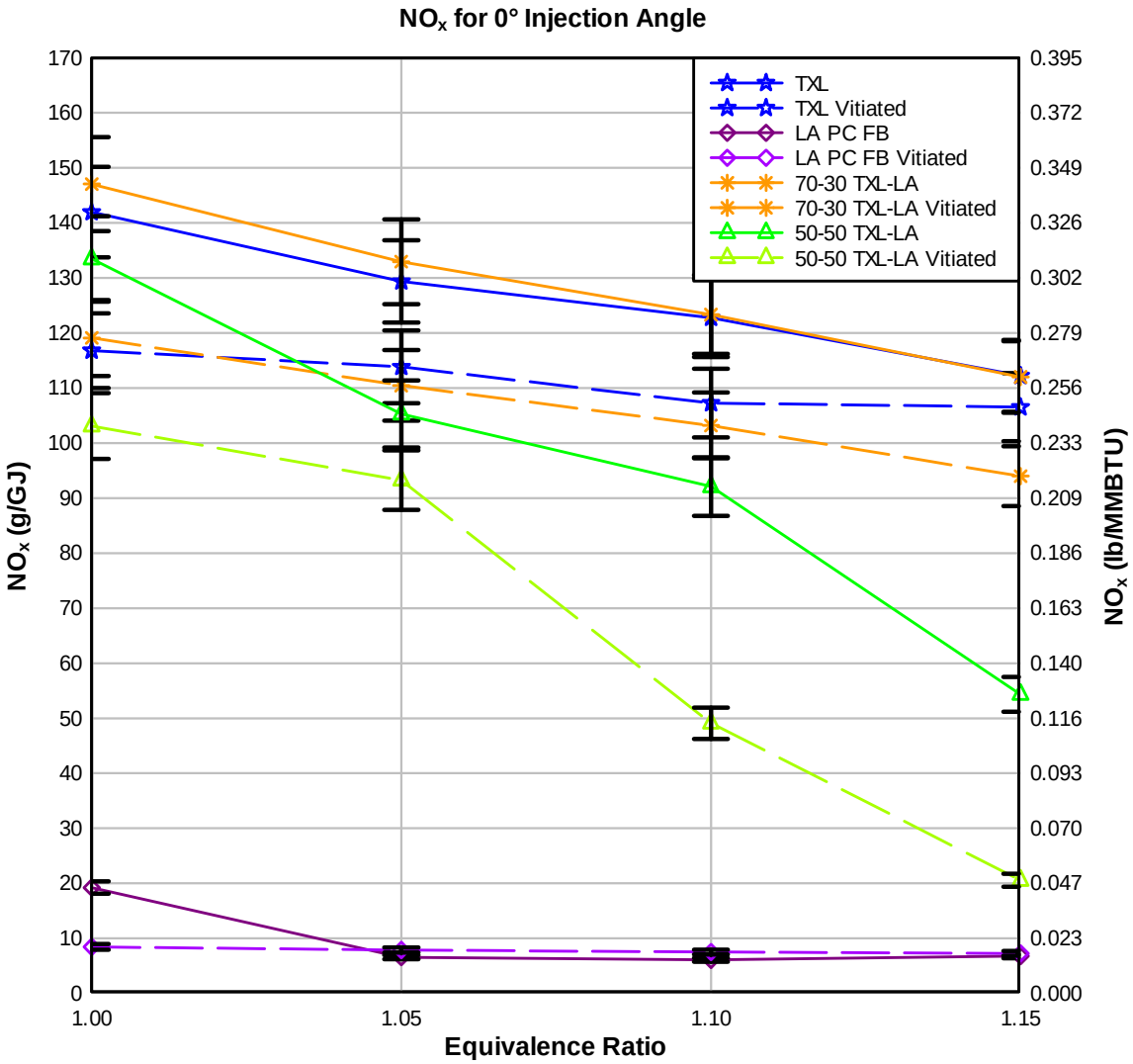

Figure 11: Comparison of vitiated vs. non-vitiated reburn experiments

Sulfur Dioxide Emissions

On a mass basis, the sulfur content of FB is similar to that found in TXL (Table 2). It is expected that the sulfur emissions measured from the use of FB as a reburn fuel will be similar to those found when TXL is fired.

The most common form of sulfur emission from coal fired power plants is sulfur dioxide (SO_2). Sulfur dioxide is water soluble and must therefore be measured with a special sample conditioning system that takes this into consideration. Unfortunately, the sample conditioning setup used was not sufficient for the accurate measurement of SO_2. Figure 12 shows some of the results obtained and the inconsistencies of the results.

CO_2 Emissions

The measured levels of CO_2 emission are very consistent with what would be expected. As can be seen in Figure 13, the level of CO_2 in the exhaust decreases slightly when the equivalence ratio increases. This trend makes sense because as the level of available oxygen decreases, CO is formed rather than CO_2.

Another distinct trend in the levels of observed CO_2 is noted in the difference between the vitiated and the non-vitiated reburn air experiments. Because nitrogen was added to the reburn air to simulate vitiation, the level of CO_2 in the exhaust was diluted. Also, as can be noted, it is more difficult to notice the downward trend of the CO_2 levels with increased equivalence ratio when vitiation is used.

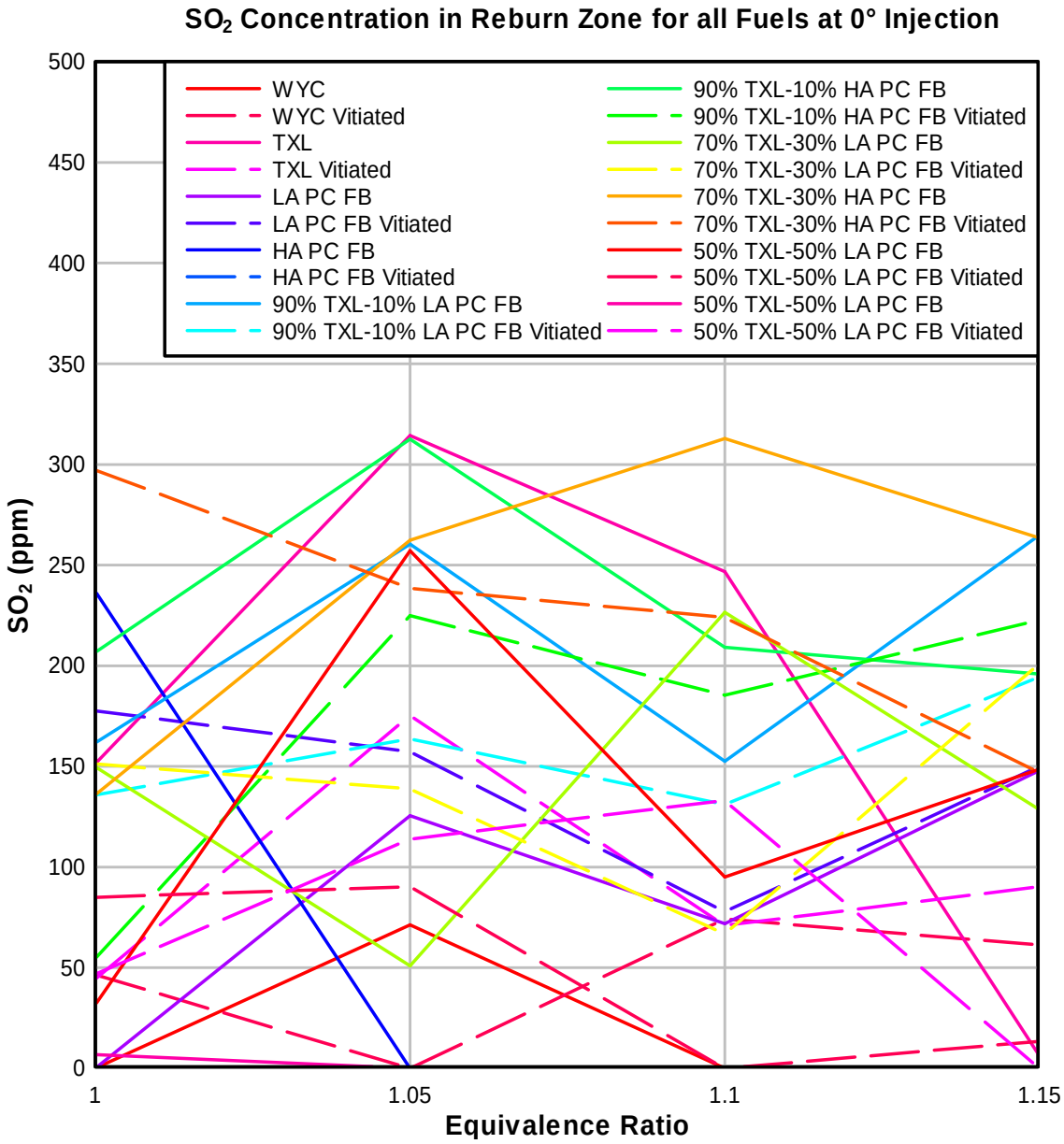

Figure 12: Sulfur dioxide measurements

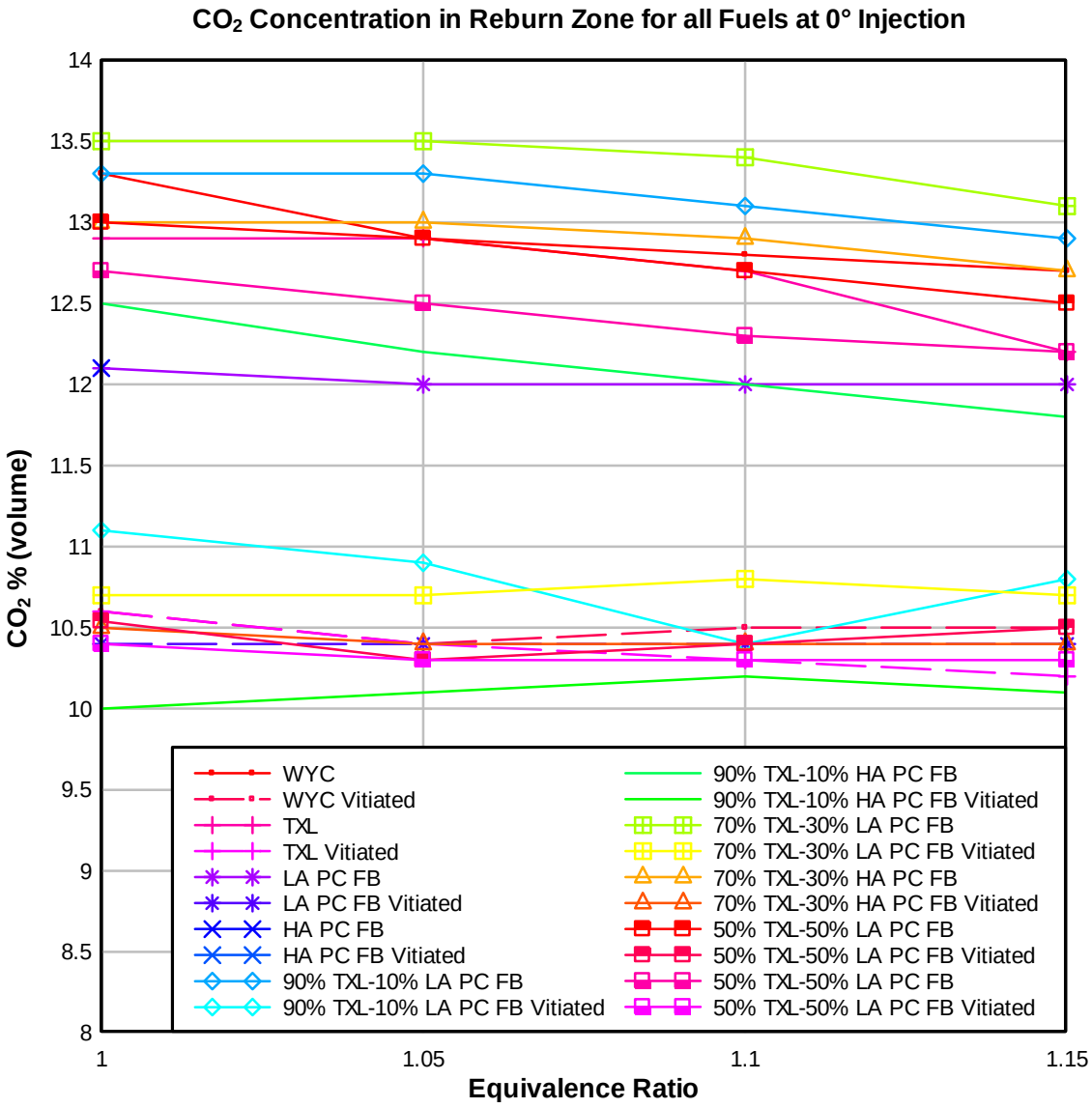

Figure 13: Carbon dioxide measurements

CO Emissions

The emission of CO from the furnace is expected to be quite high. This is because the of the fuel rich environment present in the combustion chamber. The level of CO should increase with increased equivalence ratio. Unfortunately, the CO sensor was

not operational during the majority of the experiments conducted. There is very little data available for reporting. The limited data available is seen in the figure below.

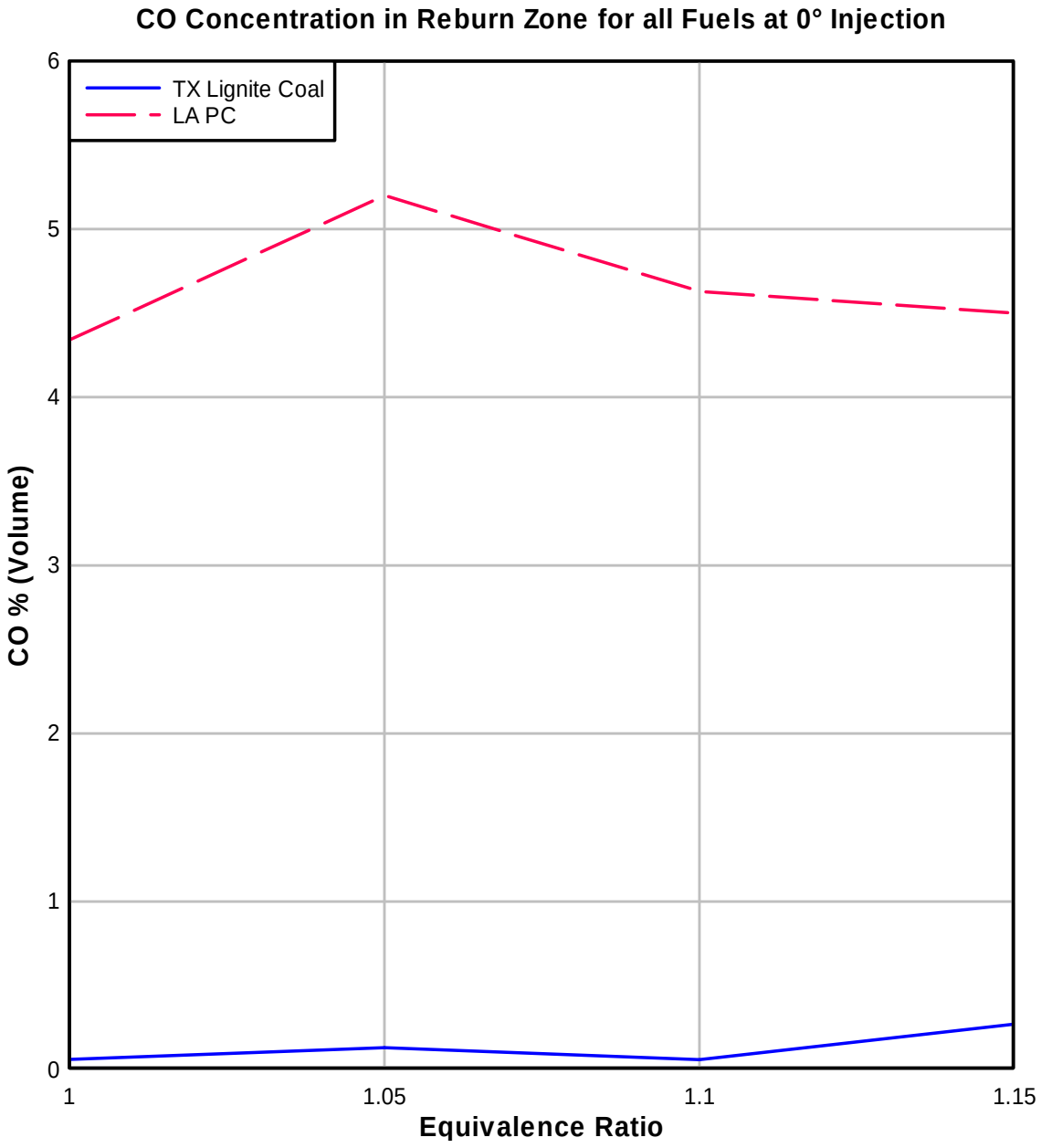

Figure 14: Carbon monoxide concentration for two fuels

Other Observations

While burning HA PC FB, the reactor clogged entirely and had to be shut down. The furnace was opened and it was found that there were severe amounts of slag on the inside of the furnace walls. Below is a picture of the debris that was built up in the area near the reburn injectors. The majority of the debris was deposited from about 4 inches above the injector to about six inches below the injectors. In Figure 15, you cannot see the reburn injectors because the slag is above the injectors. You can see two gas measurement ports in the lower right as well as two sight ports on the lower left. It is unknown whether this buildup had any effect on the NO_x reduction.

Figure 15: Top view of slag or melted ash deposits in furnace

CONCLUSIONS

After conducting the research mentioned in this report, it was determined that the optimal reburn fuel composition is pure LA PC FB. When this type of fuel is used, the effects of vitiation and injection angle are very small. If pure LA PC FB cannot be used, it would be advisable to use a 45° injection angle with vitiated reburn air and as high of percentage of LA PC FB as possible. The other conclusions are summarized below:

1. A 45° opposed flow injection of the reburn stream reduces NO_x better than a lateral injection.
2. Vitiating the air used to inject the reburn fuel reduces the level of NO_x for both the 45° injection and the lateral injection.
3. Higher equivalence ratios reduce NO_x levels to a greater extent than lower equivalence ratios.
4. LA PC FB reduces NO_x to a greater extent when compared to HA PC FB.
5. HA PC FB causes severe slag buildup in the furnace and should not be used without special consideration of the effects of the ash.
6. For blends of biomass and coal, the level of NO_x reduction increases for greater than 50% biomass by mass. Lower percentages need further experimentation to determine their effectiveness.

FUTURE IMPROVEMENTS AND RESEARCH

In order to better understand certain aspects of the conducted research and to verify the results obtained, several additional research areas are presented:

1. Control equivalence ratio better by:
    a. Obtaining electronic mass flow controllers for all of the gasses going into the reactor. Current volumetric flow meters cannot easily be compensated for temperature and pressure changes.
    b. Obtaining mass controlled solid fuel feeder system. This would allow for better mass flow control of the reburn fuel.
    c. Create a completely sealed top for the reactor to prevent air infiltration.
2. Investigate the effect of temperature on the levels of NO_x reduction obtained with LAPC FB. A method for controlling the temperature would need to be added and then the reactor temperature could be varied during the experiments.
3. Develop a method to remove the ash or part of the ash from the biomass.
4. Investigate any correlation between particle size and ash content.
6. Conduct mixing time measurements for the 45° mixing scheme.
7. Conduct experiments with Argon, CO_2, and if possible exhaust gasses to determine if the use of nitrogen to simulate vitiated air gives the same results as using actual exhaust gasses to simulate vitiation.
8. Sample gasses along the entire length of the reactor to determine the gas

composition profile of the reactor. Perform this before and after reburn fuel is used.

9. Determine if firing less biomass in the reburn zone is still able to effectively reduce NOx levels. If the level of reduction is achievable with less biomass, the feasibility of this process is expanded to even larger power plants. Try 23.42 kW (80,000 BTU/hr) in the primary zone and 5.86 kW (20,000 BTU/hr) in reburn zone and try 26.35 kW (90,000 BTU/hr) in the primary zone and 2.93 kW (10,000 BTU/hr) in reburn zone.
10. Investigate how well mixing is occurring in the reactor to ensure that there are no rich regions caused by poor mixing. If combustion is poor, develop a method to facilitate better mixing and conduct experiments again.

REFERENCES

[1] Annamalai K, Puri I. Combustion science and engineering. Orlando, FL: Taylor and Francis; 2006. Under revision.

[2] US EPA Office of Air & Radiation. Six principal pollutants. Accessed Mar 2006 http://www.epa.gov/airtrends/sixpoll.html.

[3] US EPA Office of Air & Radiation. Air Emissions Trends. Accessed May 2006 http://www.epa.gov/airtrends/2006/econ-emissions.html

[4] US EPA Office of Air & Radiation. Nitrogen oxides (NO_x) reduction under phase II of the acid rain program. Accessed Mar 2006 http://www.epa.gov/airmarkets/arp/nox/phase2.html

[5] US EPA Office of Air & Radiation. Final clean air interstate rule. Accessed Mar 2006 http://www.epa.gov/cair/rule.html

[6] Burtraw D, Evans A. The evolution of NO_x control policy for coal-fired power plants in the United States. Resources for the Future; 2003. Accessed Sept 2005 http://www.rff.org/Documents/RFF-DP-03-23.pdf

[7] Annamalai K, Thien B, Sweeten B. Co-firing of coal and cattle feedlot biomass (FB) fuels. Part II. Performance results from 30 kW (100,000) BTU/h laboratory scale boiler burner. Fuel 2003;82:1183-93.

[8] Arumugam S. Nitrogen oxides emission control through reburning with biomass in coal-fired power plants. Master's Thesis, Texas A&M University; 2004.

[9] Miller JA, Bowman CT. Mechanism and modeling of nitrogen chemistry in combustion. Prog. Energy Combust. Sci 1989;15:287-338.

[10] Williams A, Pourkashanian M, Jones JM, Rowlands L. A review of NO_x formation and reduction mechanisms in combustion systems, with particular reference to coal. J Institute of Energy 1997;70:102-13.

[11] Williams A, Pourkashanian M, Jones JM. Combustion of pulverized coal and biomass. Prog. Energy Combust. Sci. 2001;27:587-610.

[12] Bozzelli JW, Dean AM. O + NNH: a possible new route for NO_x formation in flames. Int J Chemical Kinetics 1995;27:1097-1109.

[13] Wojtowicz MA, Miknis FP, Grimes RW, Smith WW, Serio MA. Control of nitric oxide, nitrous oxide, and ammonia emissions using microwave plasmas. J Hazardous Materials 2000;74:81-9.

[14] US Department of Energy. Advanced nitrogen oxide control r&d. Accessed Mar 2006 http://www.fe.doe.gov/programs/powersystems/pollutioncontrols/overview_noxcontrols.html

[15] Xu H, Smoot LD, Tree DR, Hill SC. Prediction of nitric oxide destruction by advanced reburning. Energy & Fuels 2001;15:541-51.

[16] McCarthy K, Laux S, Grusha J. Advanced furnace air staging and burner modifications for ultra-low NO_x firing systems. Clinton, NJ: Foster Wheeler Energy Corporation.

[17] Hu YQ, Kobayashi N, Hasatani M. Effects of coal properties on recycled-NO_x reduction in coal combustion with O2/recycled flue gas. Energy Conversion and Management 2003;44:2331-40.

[18] Zongbin Z, Wen L, Jieshan Q, Xuzhen W, Baoqing L. Influence of Na and Ca on the emission of NO_x during coal combustion. Fuel 2006;85:601-6.

[19] Zongbin Z, Jieshan Q, Wen L, Haokan C, Baoqing L. Influence of mineral matter in coal on decomposition of NO over coal chars and emission of NO during char combustion. Fuel 2003;82:949-57.

[20] Savolainen K. Co-firing of biomass in coal-fired utility boilers. Applied Energy 2003;74:369-81.

[21] Adams BR, Harding NS. Reburn using biomass for NO_x control. Fuel Processing Technology 1998;54:249-63.

[22] Patumsawad S. Supplementing coal with MSW in a fluidised bed combustor. The Journal of KMITNB 2002;12(4)1-7.

[23] Spliethoff H, Hein KRG. Effect of co-combustion of biomass on emissions in pulverized fuel furnaces. Fuel Processing Technology 1998;54:189-205.

[24] Hartmann D, Kaltschmitt M. Electricity generation from solid biomass via co-combustion with coal: energy and emission balances from a German case study. Biomass and Bioenergy 1999;16:397-406.

[25] Thien B, Annamalai K. Reduction of NO Through Reburning With Coal and Feedlot Biomass. National Combustion Conference, Oakland, CA 2001; March 25-27.

[26] US EPA Office of Air and Radiation. Nitrogen Dioxide. Accessed Dec 2005. http://www.epa.gov/airtrends/nitrogen.html

APPENDIX A

MODIFICATION OF THE BURNER SETUP

The burner facility was modified for running the experiments at hand. These modifications included the casting of new refractory for the furnace, the addition of wall temperature probes, the addition of ports for heat exchanger tubes, and the lowering of the cooling water ports so that the effective length of the furnace is six feet.

Green Cast 94 was used to cast the furnace inner refractory. We first made molds for each section of the furnace. Six inch diameter foam cylinders were situated inside 10 inch diameter sections of PVC. The PVC was cut down the side and taped back together so that it could be removed after the refractory dried. Cardboard cylinders were attached to the foam and the inner wall of the PVC to make holes for the different ports on the furnace. Care must be taken to ensure that the halves of the mold are concentric and that the holes are positioned properly. This can be done by making slotted wooden frames out of wood to place at the bottom and top of each refractory mold.

After the molds were made, the Green Cast 94 was mixed in a large tub. From 10 to 20% extra water was added to the cast to facilitate the filling of the molds. The molds were filled slowly with cups. While they were being filled, the cast in the mold was kneaded with a stick to ensure that all air spaces were filled. Approximately one 55 lb bag was used for each 12 inch section of refractory.

The sections were allowed to dry and then they were fired in a furnace. As per the instruction on Green Cast 94, the refractory was slowly heated to 2350 °F and then cooled to room temperature.

After the refractory was fired, high temperature putty was used to cover the inside of the wall temperature hole. This made an approximate 1/8 inch film on the inside of the refractory wall to prevent hot gasses from coming in contact with the wall temperature thermocouple.

The furnace operates at a pressure slightly below atmospheric pressure. For this reason, the furnace must be sealed to prevent air from entering the furnace. Each steel section of the burner is sealed to the next section with silicon based caulk. The refractory is not sealed because only negligible amounts of gas will escape the refractory since the steel outer shell is sealed.

APPENDIX B

STEPS FOR CONDUCTING AN EXPERIMENT

Procedures for running an experiment are as follows (approximate time 8 hours):

1. Determine all operating conditions.
    a. main burner air requirements
    b. natural gas requirements (100% and 70%)
    c. reburn fuel requirements
    d. reburn air requirements
    e. ammonia requirements
2. Turn on temperature data acquisition system.
3. Turn on exhaust fans.
4. Turn on Primary Air to approximately 50 % of the total required airflow.
5. Turn on cooling water and cooling water sump. The cooling water flow should be between 3 and 3.5 gpm.
6. Turn on air pre-heater and wait until air leaves heater at 250 °F.
7. Start the propane torches and allow to heat furnace to 300 °F.
8. Turn on the main burner at 60% natural gas flow rate. (a fuel rich flame is more stable than a lean flame)
9. Look in view ports to ensure flame is present.
10. Allow the furnace to run for approximately one hour with propane torches lit.
11. Remove propane torches.
12. Increase the primary air to 70% of total air (100% of primary zone air).

13. Increase the natural gas flow to 70% of total heat input.
14. Allow furnace to heat for two or three more hours.
15. While preheating, calibrate the volumetric feeder system for the fuel being used.
16. After preheating, turn on ammonia to calculated flow rate.
17. Adjust ammonia and primary air to obtain desired equivalence ratio and NO_x level.
18. Turn on reburn air to desired level (air goes through venturi).
19. Turn on reburn fuel, nitrogen (for vitiation) and readjust the reburn air flow.
20. Allow furnace to reach steady state for 30 minutes.
21. Take measurements.
22. Turn off ammonia.
23. Turn off reburn fuel (leave air on to keep injector tubes cool).
24. Turn off primary air pre-heater.
25. Turn off natural gas.
26. Let the burner cool with the air on. Once the furnace cools to 200 °F, reburn air, main air, cooling water, and exhaust fans can be turned off.

APPENDIX C

FUEL PROPERTIES

Table C1: Fuel proximate and ultimate analyses for each sample analyzed

Partially Composted FB Collected Summer 2005					
SS=Soil Surface (High Ash)			FA = Fly Ash (Low Ash)		
Sample ID	**SS107**	**SS108**	**SS109**	**HA PC FB**	
Proximate (%)				**Average**	**St. Dev.**
Moisture	16.72	17.23	17.05	17.00	0.26
Ash	54.59	53.06	53.91	53.85	0.77
Volatile	25.72	26.86	24.78	25.79	1.04
Fixed C	2.97	2.85	4.26	3.36	0.78
Total	100.00	100.00	100.00	100.00	
HHV (BTU/lb)	2254	2278	2184	2238.67	48.84
Ultimate (%)					
Moisture	16.72	17.23	17.05	17.00	0.26
Carbon	14.78	15.10	14.88	14.92	0.16
Hydrogen	1.37	1.48	1.32	1.39	0.08
Nitrogen	1.11	1.14	1.13	1.13	0.02
Sulfur	0.30	0.33	0.31	0.31	0.02
Ash	54.59	53.06	53.91	53.85	0.77
Oxygen	11.13	11.66	11.40	11.40	0.27
Total	100.00	100.00	100.00	100.00	
Sample ID	**FA110**	**FA111**	**FA112**	**LA PC FB**	
Proximate (%)				**Average**	**St. Dev.**
Moisture	22.32	17.26	19.33	19.64	2.54
Ash	16.42	16.81	16.26	16.50	0.28
Volatile	50.08	54.30	52.61	52.33	2.12
Fixed C	11.18	11.63	11.80	11.54	0.32
Total	100.00	100.00	100.00	100.00	
HHV (BTU/lb)	5498	5877	5736	5703.67	191.56
Ultimate (%)					
Moisture	22.32	17.26	19.33	19.64	2.54
Carbon	32.70	34.89	33.79	33.79	1.10
Hydrogen	3.34	3.69	3.93	3.65	0.30
Nitrogen	1.89	2.03	1.99	1.97	0.07
Sulfur	0.52	0.49	0.51	0.51	0.02
Ash	16.42	16.81	16.26	16.50	0.28
Oxygen	22.81	24.83	24.19	23.94	1.03
Total	100.00	100.00	100.00	100.00	

APPENDIX D

OPERATING CONDITIONS FOR EACH EXPERIMENT

The operating conditions for the primary combustion zone were the same for all experiments. These conditions are summarized in Table 6 of the main thesis body.

The operating conditions for the reburn zone are summarized as follows:

Table D1: Reburn zone operating conditions

φ	Fuel/Blend	Injector Angle	O_2 %	Fuel (g/min)	RB Air SCFH	N_2 SCFH
1.15	Wyoming Coal	0°, 45°	12.5, 20.9	29.0	217	165
1.1	Wyoming Coal	0°, 45°	12.5, 20.9	29.0	228	172
1.05	Wyoming Coal	0°, 45°	12.5, 20.9	29.0	241	180
1	Wyoming Coal	0°, 45°	12.5, 20.9	29.0	255	189
1.15	TX Lignite Coal	0°, 45°	12.5, 20.9	36.9	220	166
1.1	TX Lignite Coal	0°, 45°	12.5, 20.9	36.9	231	174
1.05	TX Lignite Coal	0°, 45°	12.5, 20.9	36.9	244	182
1	TX Lignite Coal	0°, 45°	12.5, 20.9	36.9	258	191
1.15	LA PC	0°, 45°	12.5, 20.9	39.8	210	160
1.1	LA PC	0°, 45°	12.5, 20.9	39.8	221	168
1.05	LA PC	0°, 45°	12.5, 20.9	39.8	234	176
1	LA PC	0°, 45°	12.5, 20.9	39.8	247	184
1.15	HA PC	0°, 45°	12.5, 20.9	101.3	241	180
1.1	HA PC	0°, 45°	12.5, 20.9	101.3	253	188
1.05	HA PC	0°, 45°	12.5, 20.9	101.3	267	197
1	HA PC	0°, 45°	12.5, 20.9	101.3	282	207
1.15	90-10 Lig-LA	0°, 45°	12.5, 20.9	37.2	219	166
1.1	90-10 Lig-LA	0°, 45°	12.5, 20.9	37.2	230	173
1.05	90-10 Lig-LA	0°, 45°	12.5, 20.9	37.2	243	182
1	90-10 Lig-LA	0°, 45°	12.5, 20.9	37.2	257	191
1.15	90-10 Lig-HA	0°, 45°	12.5, 20.9	39.4	220	167
1.1	90-10 Lig-HA	0°, 45°	12.5, 20.9	39.4	231	174
1.05	90-10 Lig-HA	0°, 45°	12.5, 20.9	39.4	244	182
1	90-10 Lig-HA	0°, 45°	12.5, 20.9	39.4	258	192
1.15	70-30 Lig-LA	0°, 45°	12.5, 20.9	37.7	217	165
1.1	70-30 Lig-LA	0°, 45°	12.5, 20.9	37.7	228	172
1.05	70-30 Lig-LA	0°, 45°	12.5, 20.9	37.7	241	180
1	70-30 Lig-LA	0°, 45°	12.5, 20.9	37.7	255	189
1.15	70-30 Lig-HA	0°, 45°	12.5, 20.9	45.6	220	167
1.1	70-30 Lig-HA	0°, 45°	12.5, 20.9	45.6	232	174
1.05	70-30 Lig-HA	0°, 45°	12.5, 20.9	45.6	245	183

Table D1 continued

1	70-30 Lig-HA	0°, 45°	12.5, 20.9	45.6	259	192
1.15	50-50 Lig-LA	0°, 45°	12.5, 20.9	38.3	215	163
1.1	50-50 Lig-LA	0°, 45°	12.5, 20.9	38.3	226	171
1.05	50-50 Lig-LA	0°, 45°	12.5, 20.9	38.3	239	179
1	50-50 Lig-LA	0°, 45°	12.5, 20.9	38.3	253	188
1.15	50-50 Lig-HA	0°, 45°	12.5, 20.9	54.1	221	167
1.1	50-50 Lig-HA	0°, 45°	12.5, 20.9	54.1	233	175
1.05	50-50 Lig-HA	0°, 45°	12.5, 20.9	54.1	245	183
1	50-50 Lig-HA	0°, 45°	12.5, 20.9	54.1	259	192

APPENDIX E

FUEL NITROGEN BALANCE

Calculations were done to determine if there is sufficient nitrogen in the fuel to produce the required amount of ammonia (NH_3) needed for reducing NO_x. There were a few assumptions made when conducting these calculations. First, the amount of nitrogen converted to ammonia was assumed to be 60% and 30% for biomass and coal respectively. It was also assumed that all of the nitrogen in the fuel evolved to form NH_3, N_2, or HCN. Only the evolved ammonia was considered in the results. The bar graphs of the results show two things: the amount of reburn required to generate the amount of ammonia needed to reduce all of the NO_x and the ratio of the required amount of fuel with the supplied amount of fuel.

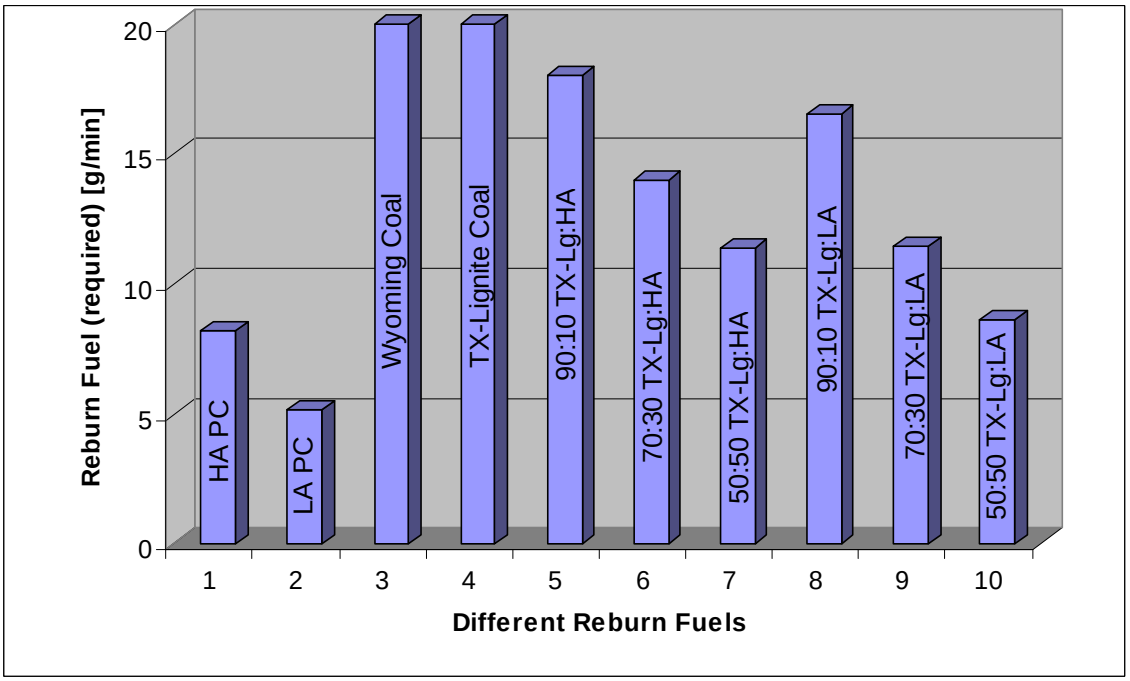

Figure E1: Amount of reburn fuel required to produce sufficient ammonia to reduce all of the NO_x in the exhaust stream

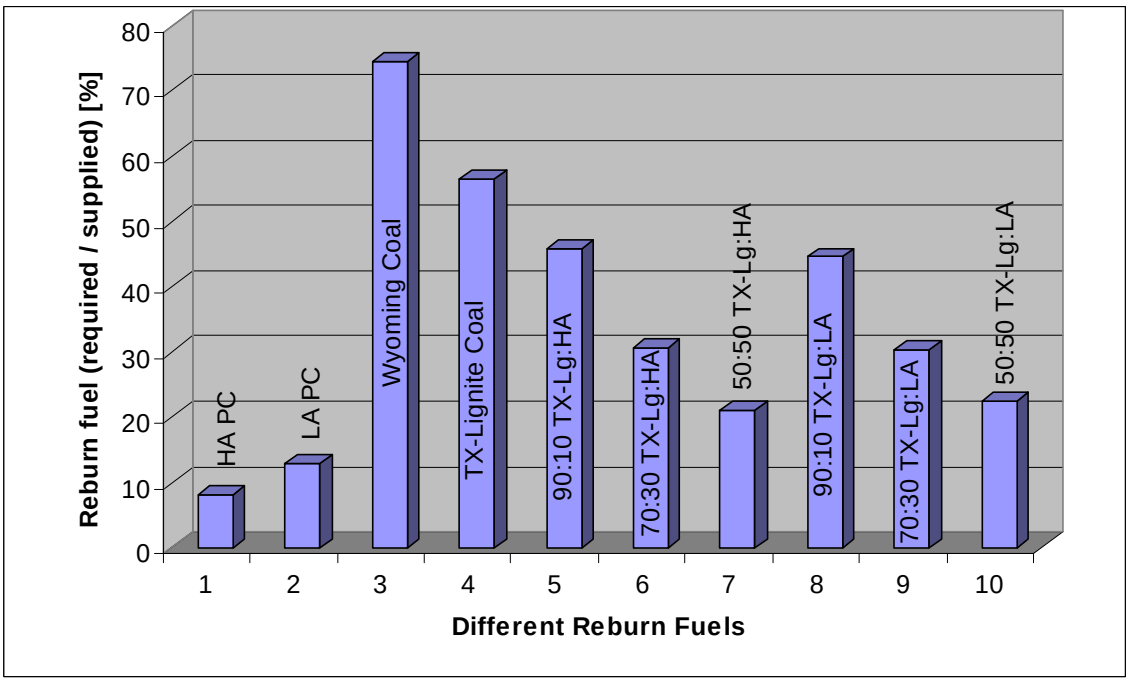

Figure E2: Ratio of the reburn fuel required to the amount of reburn fuel supplied

APPENDIX F

MIXING TIME

The mixing time in the furnace is difficult to measure and calculate. A previous thesis by Arumugam [4] was partly devoted to this topic. He used a non-reactive laminar mixing model to estimate that the mixing time for 97.3% mixed conditions was around 0.936 seconds. The model used does not account for reacting systems, turbulent flow, or for two opposed injectors. The velocity in the reactor varies from about 1.9 to 2.4 m/s depending on the fuel used and the temperature of the furnace. For the velocity found in the reactor, the calculated mixing time suggests that complete mixing never occurs.

An experiment was conducted while the reactor was still hot from an experiment. N_2 was injected in the reburn ports and air was used in the primary ports. These measurements found that after 30.5 cm (12 in), the gas streams were fully mixed. This would suggest that the mixing time in the reactor is much less than 0.936 seconds as reported by Arumugam. If we assume that the reburn injection is instantly at the speed of the main flow, it would only take 0.16 seconds. This underestimates actual mixing time since the reburn stream requires some time to increase to the free stream speed. A linear model can be used to estimate the mixing time. This model predicts that it takes twice this long or 0.32 seconds. The linear model assumes laminar flow. If there are areas of turbulence, the mixing time may be slightly shorter than the 0.32 seconds calculated from the linear mode. It can be concluded that the mixing time is between 0.16 and 0.32 seconds.

APPENDIX G

NO_X MEASUREMENT DATA

All experiments had a primary zone level of NO_x of 400 ppm. The values in the tables below represent the NO_x level in ppm measured 137 cm (54 in) after the reburn zone. The data presented in the body of the thesis is in g/GJ. The conversion from ppm to g/GJ was done using the formula $NO_{g/GJ} = \frac{NO_{ppm} \cdot 0.001 \cdot M_{NO}}{(x_{CO_2} + x_{CO}) \cdot M_{fuel} \cdot HHV_{fuel\ g/GJ}}$ where x is the mole fraction of the specified gasses in the exhaust and M is the molecular weight. The mole fractions were calculated with Equation 2 in the text. The fuel was a composite fuel composed of the primary fuel and the reburn fuel. The composite fuel was normalized to carbon. A check was performed to ensure that the above equation gave accurate results by calculating the mass flows out of the reactor with Equation 2 and using these numbers with the concentration of the gas in ppm to arrive at a total mass flow of NO. The two methods gave similar results. Some variation occurred in the third significant digit.

Table G1: NO_x measurement data for 0° injection angle

	0° Injector Angle NO_x (ppm)			
	Equivalence Ratio			
	1.00	**1.05**	**1.10**	**1.15**
WYC	342.3	328.7	294.8	267.1
WYC Vitiated	226.8	216.6	210.2	205.2
TXL	394.5	363.3	348.2	321.1
TXL Vitiated	273.2	270.7	259.0	260.9
LA PC FB	53.0	18.3	17.1	19.3
LA PC FB Vitiated	19.8	18.7	18.1	17.7
HA PC FB	120.3			
HA PC FB Vitiated				
90-10 TXL-LA	391.5	353.6	321.9	312.0
90-10 TXL-LA Vitiated	250.0	235.9	228.0	210.4
70-30 TXL-LA	407.8	372.6	349.0	319.8
70-30 TXL-LA Vitiated	278.5	262.6	249.1	230.1
50-50 TXL-LA	369.6	294.6	260.2	154.9
50-50 TXL-LA Vitiated	241.1	221.7	118.5	50.3
90-10 TXL-HA	439.8	362.6	316.2	236.1
90-10 TXL-HA Vitiated	286.2	283.8	269.0	212.5
70-30 TXL-HA	375.9	359.4	341.0	299.8
70-30 TXL-HA Vitiated	267.6	245.1	225.7	202.2
50-50 TXL-HA	374.5	348.1	340.3	322.4
50-50 TXL-HA Vitiated	320.6	272.7	262.6	252.9

Table G2: NO_x measurement data for 45° injection angle

	45° Injector Angle NO_x (ppm)			
	Equivalence Ratio			
	1.00	**1.05**	**1.10**	**1.15**
WYC	416.0	390.2	357.7	289.8
WYC Vitiated	353.6	309.4	320.3	347.1
TXL	251.8	274.2	287.7	289.8
TXL Vitiated	370.3	343.7	332.6	173.1
LA PC FB	69.5	41.2	35.0	31.1
LA PC FB Vitiated	22.8	15.9	13.7	13.6
HA PC FB	186.7	148.5	105.1	62.6
HA PC FB Vitiated	171.9	107.1	44.6	22.4
90-10 TXL-LA	426.5	327.1	272.2	89.0
90-10 TXL-LA Vitiated	282.5	261.8	209.5	67.5
70-30 TXL-LA	329.5	340.3	322.9	293.6
70-30 TXL-LA Vitiated	262.1	231.4	234.3	228.4
50-50 TXL-LA	215.0	184.9	156.2	153.2
50-50 TXL-LA Vitiated	189.6	176.4	119.2	64.4
90-10 TXL-HA	381.4	346.6	309.6	278.0
90-10 TXL-HA Vitiated	315.1	299.0	273.4	254.1
70-30 TXL-HA	405.1	348.1	318.2	264.5
70-30 TXL-HA Vitiated	284.2	267.0	239.8	226.9
50-50 TXL-HA	364.1	310.2	302.3	201.9
50-50 TXL-HA Vitiated	284.9		243.8	172.3

APPENDIX H

TEMPERATURE MEASUREMENT DATA

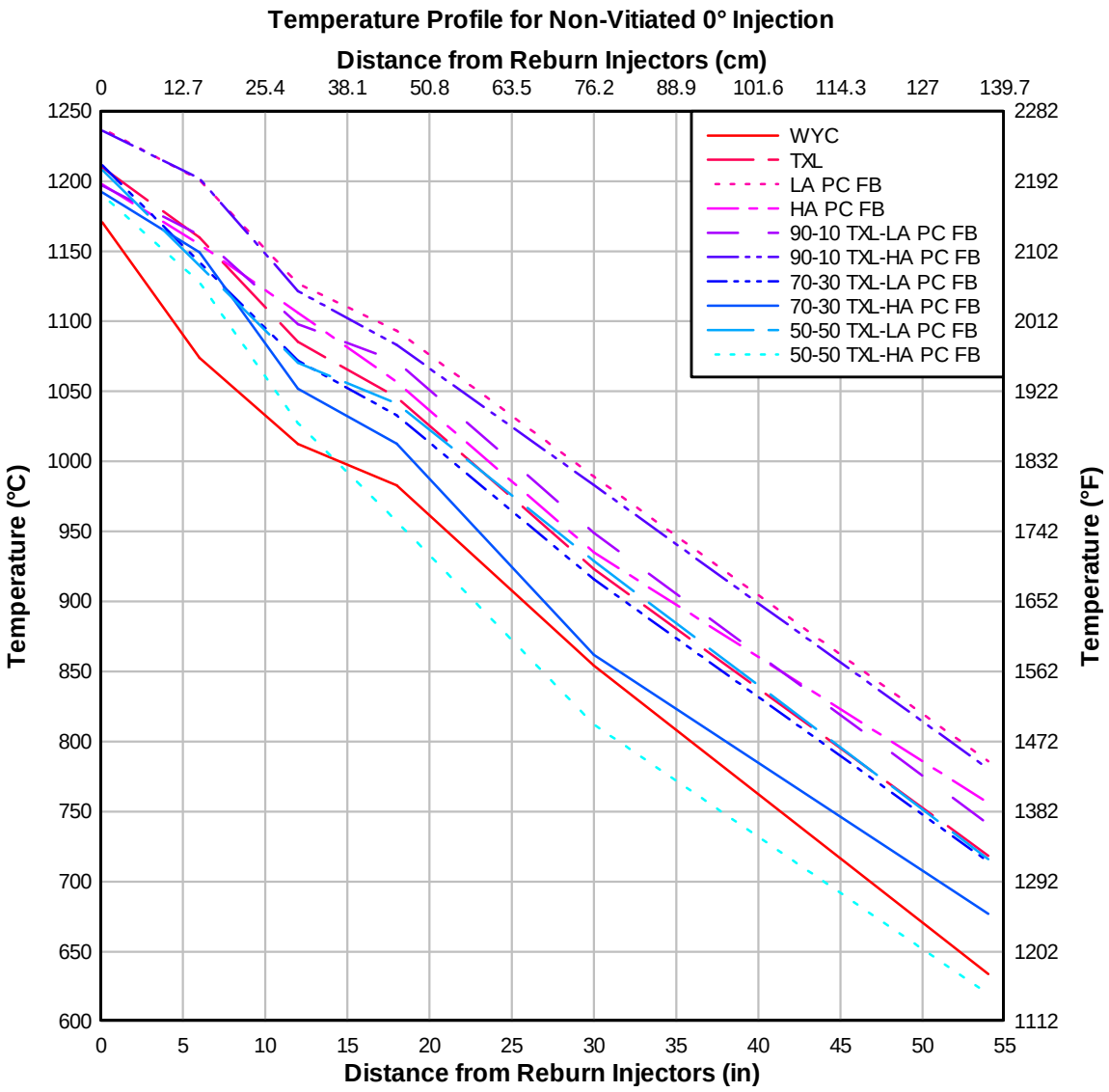

Figure H1: Temperature profile for non-vitiated 0° injection angle

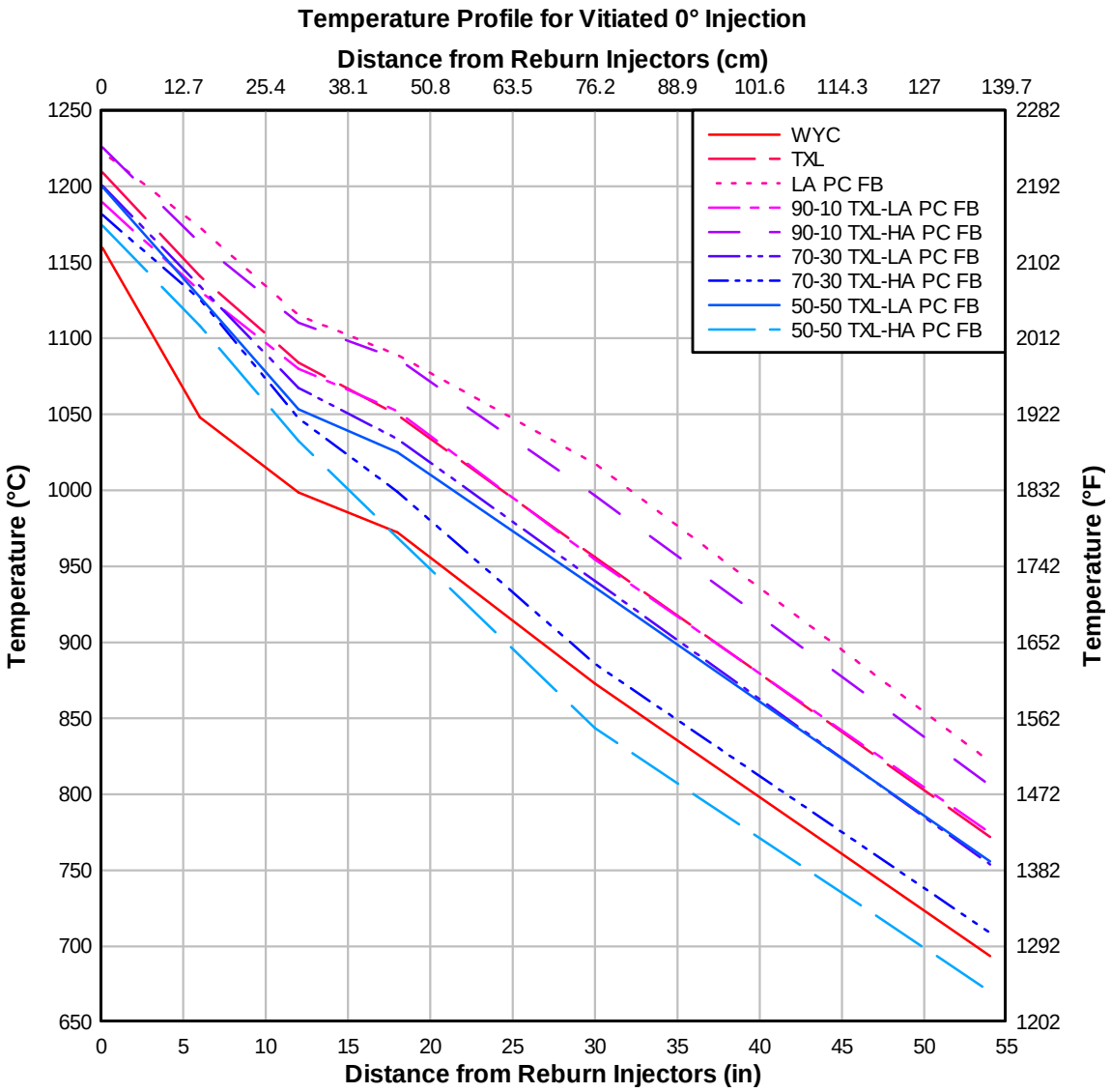

Figure H2: Temperature profile for vitiated 0° injection angle

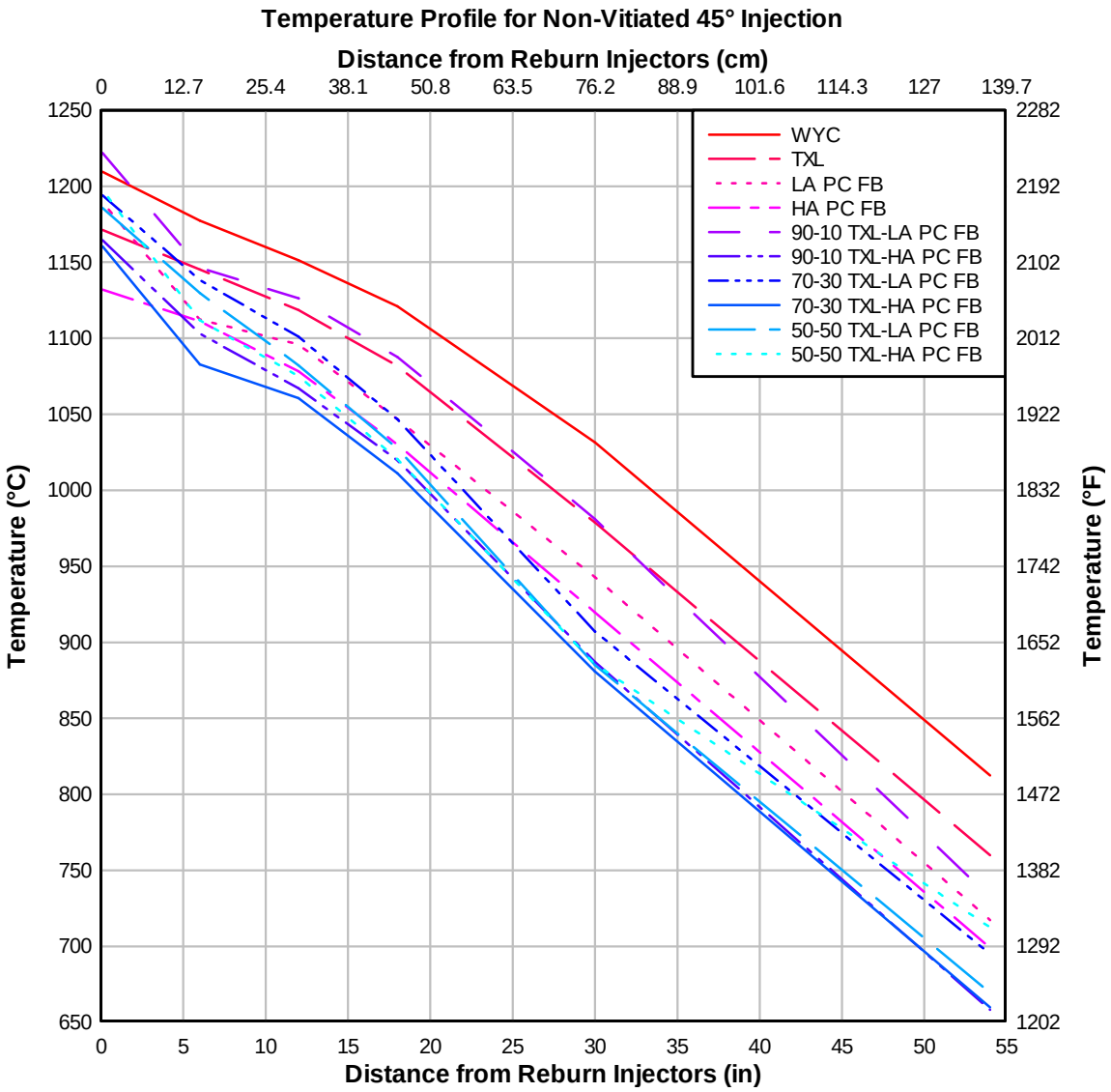

Figure H3: Temperature profile for non-vitiated 45° injection angle

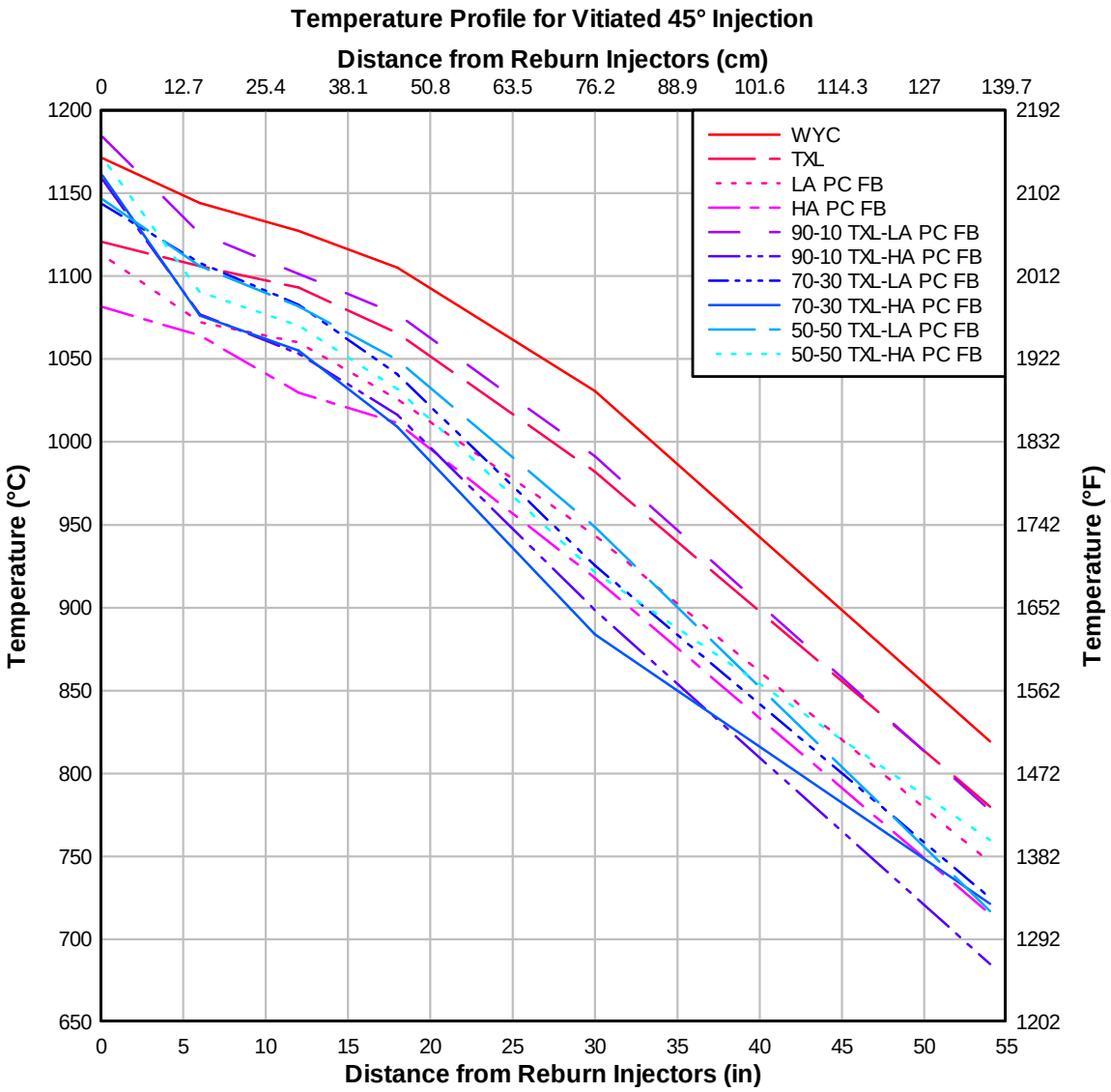

Figure H4: Temperature profile for vitiated 45° injection angle

Table H1: Wall temperature measurements for 0° reburn injection

0° Injection Wall Temperature Measurements			
	Distance Below Reburn Injection		
Fuel	**45.72cm (18 in)**	**91.44 cm (36 in)**	**137.16 cm (54 in)**
WYC	1540	1244	951
WYC Vitiated	1577	1295	999
TXL	1696	1396	1065
TXL Vitiated	1780	1524	1193
LA PC FB FB	1846	1590	1230
LA PC FB FB Vitiated	1862	1625	1275
HA PC FB FB	1762	1469	1147
HA PC FB FB Vitiated	No Data	No Data	No Data
90% TXL-10% LA PC FB FB	1760	1466	1123
90% TXL-10% LA PC FB FB Vitiated	1775	1507	1174
90% TXL-10% HA PC FB FB	1810	1563	1235
90% TXL-10% HA PC FB FB Vitiated	1843	1622	1301
70% TXL-30% LA PC FB FB	1678	1384	1065
70% TXL-30% LA PC FB FB Vitiated	1733	1467	1146
70% TXL-30% HA PC FB FB	1612	1297	989
70% TXL-30% HA PC FB FB Vitiated	1670	1389	1080
50% TXL-50% LA PC FB FB	1682	1342	1089
50% TXL-50% LA PC FB FB Vitiated	1709	1459	1151
50% TXL-50% LA PC FB FB	1509	1157	865
50% TXL-50% LA PC FB FB Vitiated	1585	1251	949

Table H2: Wall Temperature Measurements for 45° Reburn Injection

45° Injection Wall Temperature Data			
	Distance Below Reburn Injection		
Fuel	**45.72cm (18 in)**	**91.44 cm (36 in)**	**137.16 cm (54 in)**
WYC	1814	1657	1341
WYC Vitiated	2131	1672	1364
TXL	1810	1551	1245
TXL Vitiated	1816	1591	1292
LA PC FB FB	1727	1476	1189
LA PC FB FB Vitiated	1752	1539	1249
HA PC FB FB	1744	1454	1160
HA PC FB FB Vitiated	1749	1500	1218
90% TXL-10% LA PC FB FB	1835	1566	1245
90% TXL-10% LA PC FB FB Vitiated	1857	1627	1309
90% TXL-10% HA PC FB FB	1692	1347	1034
90% TXL-10% HA PC FB FB Vitiated	1729	1412	1097
70% TXL-30% LA PC FB FB	1721	1365	1058
70% TXL-30% LA PC FB FB Vitiated	1754	1435	1124
70% TXL-30% HA PC FB FB	1667	1306	992
70% TXL-30% HA PC FB FB Vitiated	1694	1346	1021
50% TXL-50% LA PC FB FB	1669	1307	1015
50% TXL-50% LA PC FB FB Vitiated	1775	1507	1191
50% TXL-50% LA PC FB FB	1705	1360	1032
50% TXL-50% LA PC FB FB Vitiated	1753	1456	1131

APPENDIX I

MEASUREMENT EQUIPMENT AND MEASUREMENT ERROR

The Lancom III Combustion Gas Analyzer was used for all measurements. The instrument measured CO_2, SO_2, NO_2, NO, O_2, and C_xH_y. For further information on this analyzer, visit Land Instrument's website at www.landinstruments.com.

The gas flow rates were all controlled with Rota-meters with the exception of the natural gas flow rate. It was controlled by the use of a digital flow controller made by OMEGA Inc. The solid fuel was fed to the system with a volumetric feeder. The feed rate was calibrated for each fuel before experimentation.

The measurement error for all equipment is outlined in Table H1. This information was used to develop measurement error bars for the generated data. It was determined that the NO_x readings have an error of +/- 5.8% of the reading. There is also an error associated with the equivalence ratio used in each experiment. This error varies slightly for each fuel due to the error associated with the solid fuel feeder. The equivalence ratio measurement error calculation for pure coal determined that the equivalence ratio could vary by +/- 0.023.

Table I1: Measurement errors for various measurements used in experiments

Measurement (units)	**Measurement Error**
Rotameter – 20 to 200 SCFH Air	+/- 2.5 SCFH
Rotameter – 0 to 0.5 SCFH NH_3	+/- 0.01 SCFH
Solid Fuel Feeder	+/- 1 g/min
NO (ppm)	+/- 2% of reading
CO (% volume)	+/- 2% of reading
CO_2 (% volume)	+/- 2% of reading
SO_2 (ppm)	+/- 2% of reading
O_2 (% Excess Air)	+/- 2% of reading

VITA

Paul Gordon Goughnour completed his bachelor's degree in mechanical engineering in April 2004 from Brigham Young University in Provo, UT. During his education and after graduating from BYU he worked on the product development team at Industrial Training Zone. Paul then accepted a graduate fellowship at Texas A&M University in College Station, TX and received his master's degree in August 2006. Paul may be contacted by mail at 1007 Auburn View Lane, Fresno, TX 77545 or by email at paul.goughnour@gmail.com.